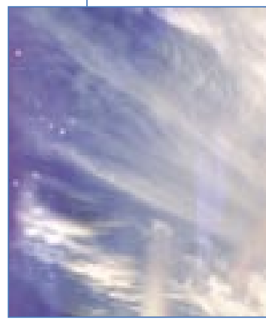


2 Approach to Earth System Science

Extensive observations interpreted carefully and taking advantage of rapidly improving understanding of sensors and of the character of observed variables, allow estimates of many Earth attributes and contribute critical understanding of the forces acting on the Earth, responses, and variations in the fundamental processes involved. But observational approaches alone are inadequate for addressing the fundamental Earth science questions confronting NASA. Many aspects of Earth system change happen too slowly, and many processes, such as those occurring in soils or the deep oceans, cannot be observed directly over large areas. Models provide a means of estimating forces and changes that cannot be observed directly and are a critical means of expressing our understanding of the complex subsystems of the Earth and how these interact and respond as a highly coupled system. Models link Earth observations to predictions.

The five fundamental questions described in the previous section represent a broad framework of Earth system science and a paradigm for a flexible research program focusing on Earth observations, modeling, analysis, and prediction. Table 2.1 lists specific questions that organize and direct NASA Earth science research. NASA brings unique capabilities for Earth observation from space to bear on these questions.

2.1 Research Focus Areas

NASA seeks comprehensive understanding of Earth system change, and to accomplish this, the NASA Earth science research program is necessarily broad and interdisciplinary. While NASA relies heavily on specialized expertise and resources in Earth science, its research initiatives cut across traditional scientific disciplines. To be effective in addressing the full hierarchy of questions in table 2.1, while continuing longer-term efforts to develop Earth system models and predictive capabilities, NASA Earth science research is organized within six interdisciplinary focus areas: Atmospheric Com-

Table 2.1

Hierarchy of science questions.
Overall: How is the Earth changing and what are the consequences for life on Earth?
How is the global Earth system changing? (Variability)
How are global precipitation, evaporation, and the cycling of water changing? How is the global ocean circulation varying on interannual, decadal, and longer time scales? How are global ecosystems changing? How is atmospheric composition changing? What changes are occurring in the mass of the Earth's ice cover? How is the Earth's surface being transformed by naturally occurring tectonic and climatic processes?
What are the primary forcings of the Earth system? (Forcing)
What trends in atmospheric constituents and solar radiation are driving global climate? What changes are occurring in global land cover and land use, and what are their causes? What are the motions of the Earth's interior, and how do they directly impact our environment?
How does the Earth system respond to natural and human-induced changes? (Response)
What are the effects of clouds and surface hydrologic processes on Earth's climate? How do ecosystems, land cover and biogeochemical cycles respond to and affect global environmental change? How can climate variations induce changes in the global ocean circulation? How do atmospheric trace constituents respond to and affect global environmental change? How is global sea level affected by natural variability and human-induced change in the Earth system?
What are the consequences of change in the Earth system for human civilization? (Consequences)
How are variations in local weather, precipitation and water resources related to global climate variation? What are the consequences of land cover and land use change for human societies and the sustainability of ecosystems? What are the consequences of climate change and increased human activities for coastal regions? What are the effects of global atmospheric chemical and climate changes on regional air quality?
How will the Earth system change in the future, and how can we improve predictions through advances in remote sensing observations, data assimilation and modeling? (Prediction)
How can weather forecast duration and reliability be improved? How can predictions of climate variability and change be improved? How will future changes in atmospheric composition affect ozone, climate, and global air quality? How will carbon cycle dynamics and terrestrial and marine ecosystems change in the future? How will water cycle dynamics change in the future? How can our knowledge of earth surface change be used to predict and mitigate natural hazards?

position, Carbon Cycle and Ecosystems, Climate Variability and Change, Earth Surface and Interior, Water and Energy Cycle, and Weather.

These six focus areas include research that not only addresses the challenging hierarchy of science questions in table 2.1 but drives the development of an Earth observing capability and associated Earth system models as well. While a variety of focus areas can be proposed to organize Earth science research, specific NASA research programs fit well within the six currently adopted by the agency and align well within the major elements of U.S. and international programs.

Natural linkages underlie many fundamental Earth system processes, and multiple focus areas have interests in many of the questions and issues in table 2.1. For example, the interactions between carbon and water in photosynthesis and evapotranspiration influence large-scale exchanges between the atmosphere and land surface so strongly that the Carbon Cycle and Ecosystems focus area and the Water and Energy Cycle focus area find common ground in many aspects of their efforts. Thus, interaction and coordination between focus areas is essential and occurs routinely as NASA solicits and coordinates Earth science research. NASA's emphasis on global observations and on Earth system science force coordinated effort across the focus areas. The Earth system modeling and analysis effort described in a subsequent section draws on scientific results, data products, and models developed within all focus areas and maintains constant integration and synthesis.

Descriptions of the six focus areas follow. Each focus area emphasizes selected questions from the list in table 2.1, but typically, research within multiple focus areas must be linked in order to address many of these questions. Roadmaps summarize the technology, observations, modeling, field campaigns, basic research, and partnerships needed over time to achieve the long-term goals for each focus area. Where focus areas collaborate closely, their roadmaps contain related items.

Each roadmap diagram portrays a strategy for a decade of progress from "where we are now" toward a goal of "where we want to be" in 2015. This strategy has at its base a foundation of systematic observations and steady improvements in understanding and modeling capabilities. Specific programmatic elements, representing major investments of resources, are layered on top of this foundation. Systematic observations are shown across the bottom of the diagram. Just continuing research utilizing these observations will extend knowledge as indicated by the upward trend; the same is true for the associated improvements immediately above the observations. Focus area programmatic elements, indicated by the horizontal arrows within the roadmap, represent new activities that

Figure 1.2

Specific Science Questions

Variability	Forcing	Response	Consequence	Prediction
Precipitation, evaporation and cycling of water changing?	Atmospheric constituents and solar radiation on climate?	Clouds and surface hydrological processes on climate?	Weather variation related to climate variation?	Weather forecasting improvement?
Global ocean circulation varying?	Changes in land cover and land use?	Ecosystems, land cover and biogeochemical cycles?	Consequences of land cover and land use change?	Improve prediction of climate variability and change?
Global ecosystems changing?	Motions of the Earth and Earth's interior?	Changes in global ocean circulation?	Coastal region impacts?	Ozone, climate and air quality impacts of atmospheric composition?
Atmospheric composition changing?		Atmospheric trace constituents responsess?	Regional air quality impacts?	Carbon cycle and ecosystem change?
Ice cover mass changing?		Sea level affected by Earth system change?		Change in water cycle dynamics?
Earth surface transformation?				Predict and mitigate natural hazards from Earth surface change?

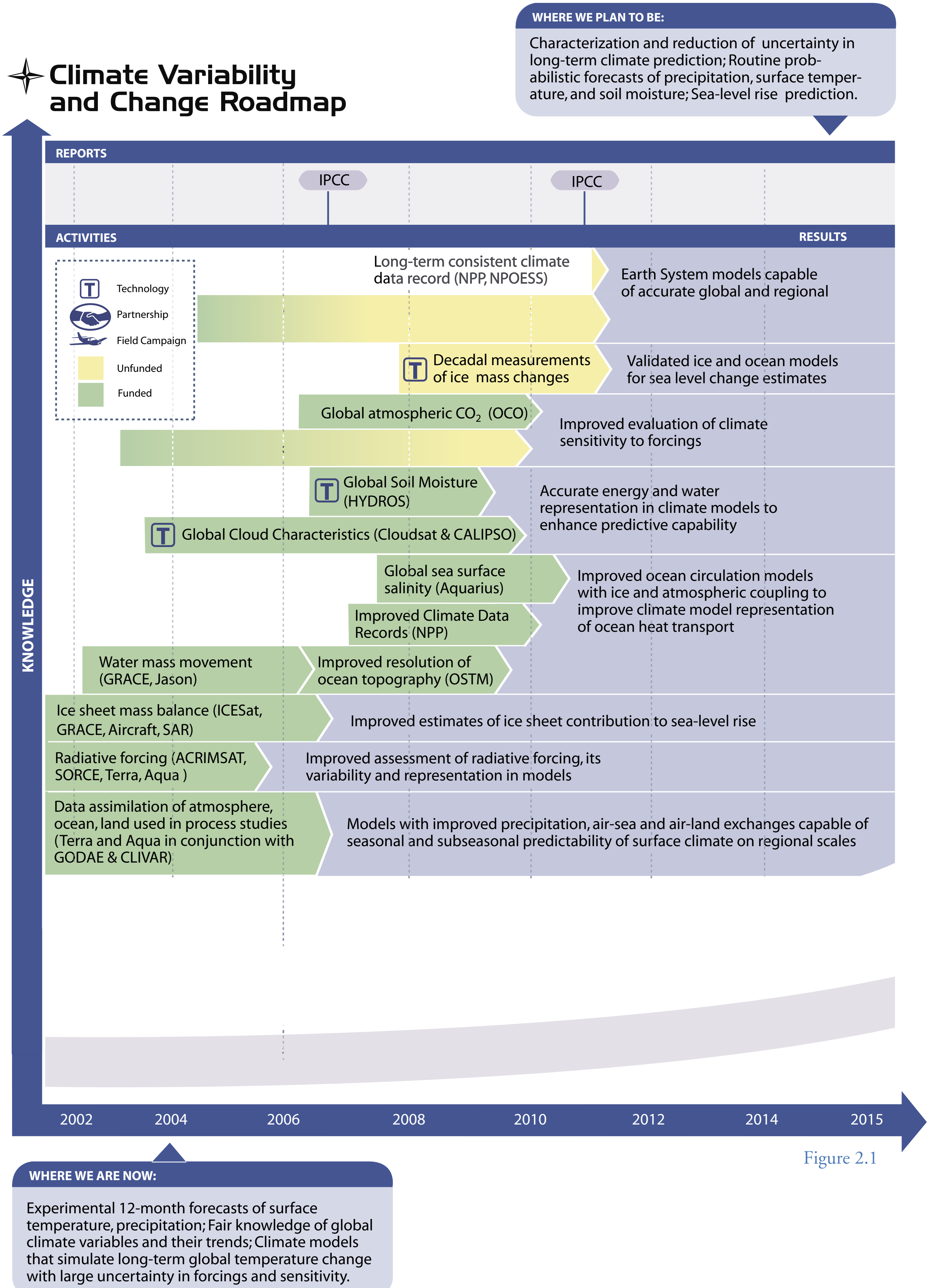

Climate Variability and Change Roadmap
WHERE WE PLAN TO BE:
Characterization and reduction of uncertainty in long-term climate prediction; Routine probabilistic forecasts of precipitation, surface temperature, and soil moisture; Sea-level rise prediction.
REPORTS
IPCC
IPCC
ACTIVITIES
RESULTS
Technology
Partnership
Field Campaign
Unfunded
Funded
Long-term consistent climate data record (NPP, NPOESS)
Earth System models capable of accurate global and regional
Decadal measurements of ice mass changes
Validated ice and ocean models for sea level change estimates
Global atmospheric CO_2 (OCO)
Improved evaluation of climate sensitivity to forcings
Global Soil Moisture (HYDROS)
Global Cloud Characteristics (Cloudsat & CALIPSO)
Accurate energy and water representation in climate models to enhance predictive capability
Global sea surface salinity (Aquarius)
Improved Climate Data Records (NPP)
Improved ocean circulation models with ice and atmospheric coupling to improve climate model representation of ocean heat transport
Water mass movement (GRACE, Jason)
Improved resolution of ocean topography (OSTM)
Ice sheet mass balance (ICESat, GRACE, Aircraft, SAR)
Improved estimates of ice sheet contribution to sea-level rise
Radiative forcing (ACRIMSAT, SORCE, Terra, Aqua)
Improved assessment of radiative forcing, its variability and representation in models
Data assimilation of atmosphere, ocean, land used in process studies (Terra and Aqua in conjunction with GODAE & CLIVAR)
Models with improved precipitation, air-sea and air-land exchanges capable of seasonal and subseasonal predictability of surface climate on regional scales
KNOWLEDGE
2002
2004
2006
2008
2010
2012
2014
2015
WHERE WE ARE NOW:
Experimental 12-month forecasts of surface temperature, precipitation; Fair knowledge of global climate variables and their trends; Climate models that simulate long-term global temperature change with large uncertainty in forcings and sensitivity.

Figure 2.1

will greatly increase knowledge beyond that which would be derived from just continuing the analysis of the systematic observations and through the improvements. These program elements are what enable the focus area to fully achieve its goals by 2015. The program elements are phased in time based on focus area priorities and technological readiness, as well as other programmatic criteria described in Section 4 to follow. Elements begin with conceptualization, including specification of program or mission requirements and the development of approaches. Programs end or missions launch at the point of the arrow (to the right) on the element line. Scientific outcomes follow and are described in the block to the right of the arrow.

The colors of the programmatic elements indicate their funding status, with blended colors to express partial or uncertain funding. Aircraft icons imply that an element includes an experiment or field campaign, which may or may not involve aircraft. A "T" icon means that technological development is required prior to undertaking an element. The joined hands icon signifies a significant national or international partnership in an element. Focus area research contributes to major reports and assessments; these are indicated in ovals along the top of the roadmaps. Note that multiple focus areas contribute to many of these major products.

2.1.1 Climate Variability and Change

Climate change can have tremendous consequences for the lives and livelihoods of individuals as well as for entire civilizations. While favorable climate is believed to have facilitated the "cradle of civilization" that sprang from the fertile lands of Mesopotamia, past climate change has displaced or even eliminated cultures and societies. One of the most notable displaced the Vikings, who in the late twelfth century abandoned villages and towns in Greenland and Iceland after temperatures cooled by only a few degrees centigrade.

Changes in climate can benefit or impact societies, and our ability to mitigate, adapt to, or capitalize on climatic change depends critically on understanding the processes at work and our ability to predict their future behavior. NASA's role in characterizing, understanding, and predicting climate variability and change focuses on global observations of the more slowly responding components of the system (primarily oceans and ice), naturally occurring processes and human activities that affect climate, and their interactions within the Earth system. The Climate Variability and Change Focus Area organizes NASA research to address the following major questions:

- How is the global ocean circulation varying on interannual, decadal, and longer time scales?
- What changes are occurring in the mass of the Earth's ice cover?
- How can climate variations induce changes in the global ocean circulation?
- How is global sea level affected by natural variability and human-induced change in the Earth system?
- How can predictions of climate variability and change be improved?

As depicted in the focus area roadmap (figure 2.1), climate variability and change research incorporates comprehensive observations into models that can accurately predict climatic change over seasonal, interannual, decadal, and longer time periods. NASA's research in this and the following three science focus areas is tightly coupled to the priorities of the interagency U.S. Çlimate Change Science Program.

The oceans are a major part of the climate system, and a unique NASA contribution to climate science is the near-global coverage of observations from space of selected ocean properties every 2 to 10 days. Additionally, NASA provides observations of the vast expanses of polar ice on the temporal and spatial scales necessary to detect change and sampling of the other critical elements of the climate system that link climate to other focus areas such as cloud distribution, snow cover, surface temperatures, and humidity characteristics.

The Nation benefits from NASA's substantial investments to characterize and understand the nature and variability of the climate system. Current capabilities include global measurements of sea surface topography, ocean vector winds, ice topography and motion, and mass movements of the Earth's fluid envelope and cryosphere. Critically-needed new measurements include sea-ice thickness, sea-ice snow cover, decadal change in ice-mass over land, and sea-surface salinity.

Sea ice modulates the exchange of energy, moisture, and momentum between the ocean and atmosphere and affects ocean circulation through brine rejection when formed. As such, its thickness and spatial characteristics need to be well understood. NASA investments have enabled monitoring of the spatial characteristics of sea ice, but the critical thickness dimension needs to be observed in order to sufficiently quantify the role of sea ice in the climate system and how changes in ice cover affect ocean circulation.

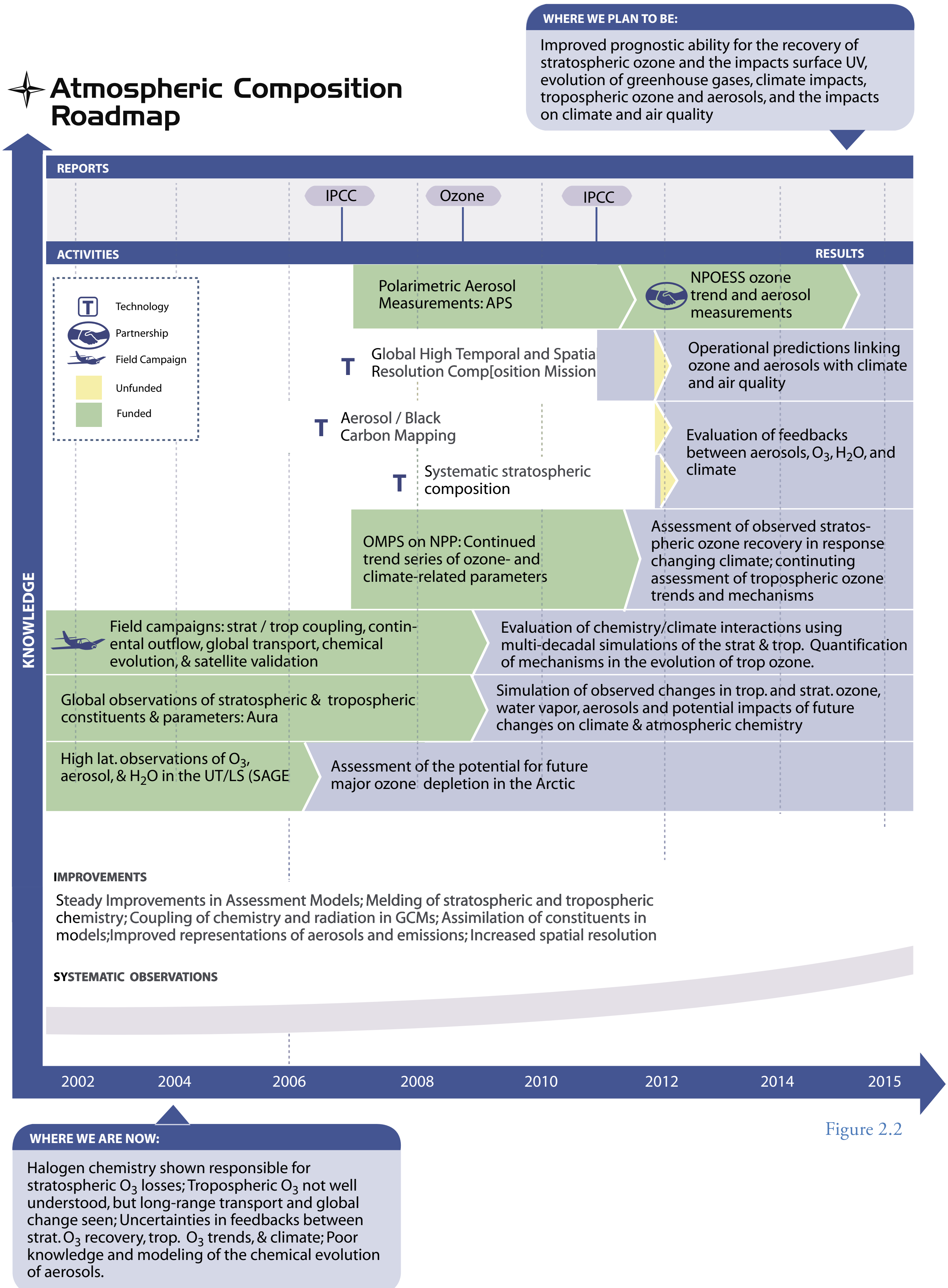

Atmospheric Composition Roadmap
WHERE WE PLAN TO BE:
Improved prognostic ability for the recovery of stratospheric ozone and the impacts surface UV, evolution of greenhouse gases, climate impacts, tropospheric ozone and aerosols, and the impacts on climate and air quality
REPORTS
IPCC
Ozone
IPCC
ACTIVITIES
RESULTS
Technology
Partnership
Field Campaign
Unfunded
Funded
Polarimetric Aerosol Measurements: APS
NPOESS ozone trend and aerosol measurements
Global High Temporal and Spatia Resolution Comp[osition Mission
Operational predictions linking ozone and aerosols with climate and air quality
Aerosol / Black Carbon Mapping
Evaluation of feedbacks between aerosols, O_3, H_2O, and climate
Systematic stratospheric composition
OMPS on NPP: Continued trend series of ozone- and climate-related parameters
Assessment of observed stratospheric ozone recovery in response changing climate; continuting assessment of tropospheric ozone trends and mechanisms
Field campaigns: strat / trop coupling, continental outflow, global transport, chemical evolution, & satellite validation
Evaluation of chemistry/climate interactions using multi-decadal simulations of the strat & trop. Quantification of mechanisms in the evolution of trop ozone.
Global observations of stratospheric & tropospheric constituents & parameters: Aura
Simulation of observed changes in trop. and strat. ozone, water vapor, aerosols and potential impacts of future changes on climate & atmospheric chemistry
High lat. observations of O_3, aerosol, & H_2O in the UT/LS (SAGE
Assessment of the potential for future major ozone depletion in the Arctic
KNOWLEDGE
IMPROVEMENTS
Steady Improvements in Assessment Models; Melding of stratospheric and tropospheric chemistry; Coupling of chemistry and radiation in GCMs; Assimilation of constituents in models; Improved representations of aerosols and emissions; Increased spatial resolution
SYSTEMATIC OBSERVATIONS
2002
2004
2006
2008
2010
2012
2014
2015
WHERE WE ARE NOW:
Halogen chemistry shown responsible for stratospheric O_3 losses; Tropospheric O_3 not well understood, but long-range transport and global change seen; Uncertainties in feedbacks between strat. O_3 recovery, trop. O_3 trends, & climate; Poor knowledge and modeling of the chemical evolution of aerosols.

Figure 2.2

Characterizing snow depth on sea ice is also crucial to understanding the extent to which the sea-ice cover influences the broader climate. Snow is a much more effective insulator than ice, so from an energy exchange perspective, it is as important, if not more so, than sea ice. We currently have crude means of estimating snow depth on sea ice, but substantial research is needed to develop robust measurements of this parameter. Current measurements of ice mass over land must be followed by future missions to determine longer-term change in ice mass and its contribution to sea level. Ancillary measurements (e.g., ice thickness and velocity) are required to understand the mechanisms that drive these changes. Companion focus areas address complementary measurements: soil moisture, atmospheric aerosols, aerosol-cloud-radiation feedbacks, and atmospheric CO_2.

Understanding interactions within the climate system also requires strong modeling and analysis efforts. The climate system is dynamic and complex, and modeling is the only way we can effectively integrate the observations and current knowledge of individual components to fully characterize current conditions and underlying mechanisms as well as to project the future states of the climate system. This requires a concerted effort both to improve the representation of physical, chemical and biological processes in models, and to incorporate observations into climate models through data assimilation and other techniques. The ultimate objective is to enable a predictive capability of climate change on time scales ranging from seasonal to multi-decadal.

2.1.2 Atmospheric Composition

Atmospheric composition determines air quality and affects weather, climate, and critical constituents such as ozone. Exchanges with the atmosphere link terrestrial and oceanic pools within the carbon cycle and other biogeochemical cycles. Solar radiation affects atmospheric chemistry and is thus a critical factor in atmospheric composition. The ability of the atmosphere to integrate surface emissions globally on time scales from weeks to years couples several environmental issues including global ozone depletion and recovery and its impact on surface ultraviolet radiation, climate forcing by radiatively active gases and aerosols, and global air quality. Thus, atmospheric chemistry and associated composition are a central aspect of Earth system dynamics.

The research strategy for furthering our understanding of atmospheric composition is geared to providing an improved prognostic capability for the recovery of stratospheric ozone and its impacts on surface ultraviolet radiation, the evolution of greenhouse gases and their impacts on climate, and the evolution of tropospheric ozone and aerosols and their impacts on climate and air quality. Toward this end, research within the atmospheric composition focus area addresses the following science questions:

- How is atmospheric composition changing?
- What trends in atmospheric constituents and solar radiation are driving global climate?
- How do atmospheric trace constituents respond to and affect global environmental change?
- What are the effects of global atmospheric chemical and climate changes on regional air quality?
- How will future changes in atmospheric composition affect ozone, climate, and global air quality?

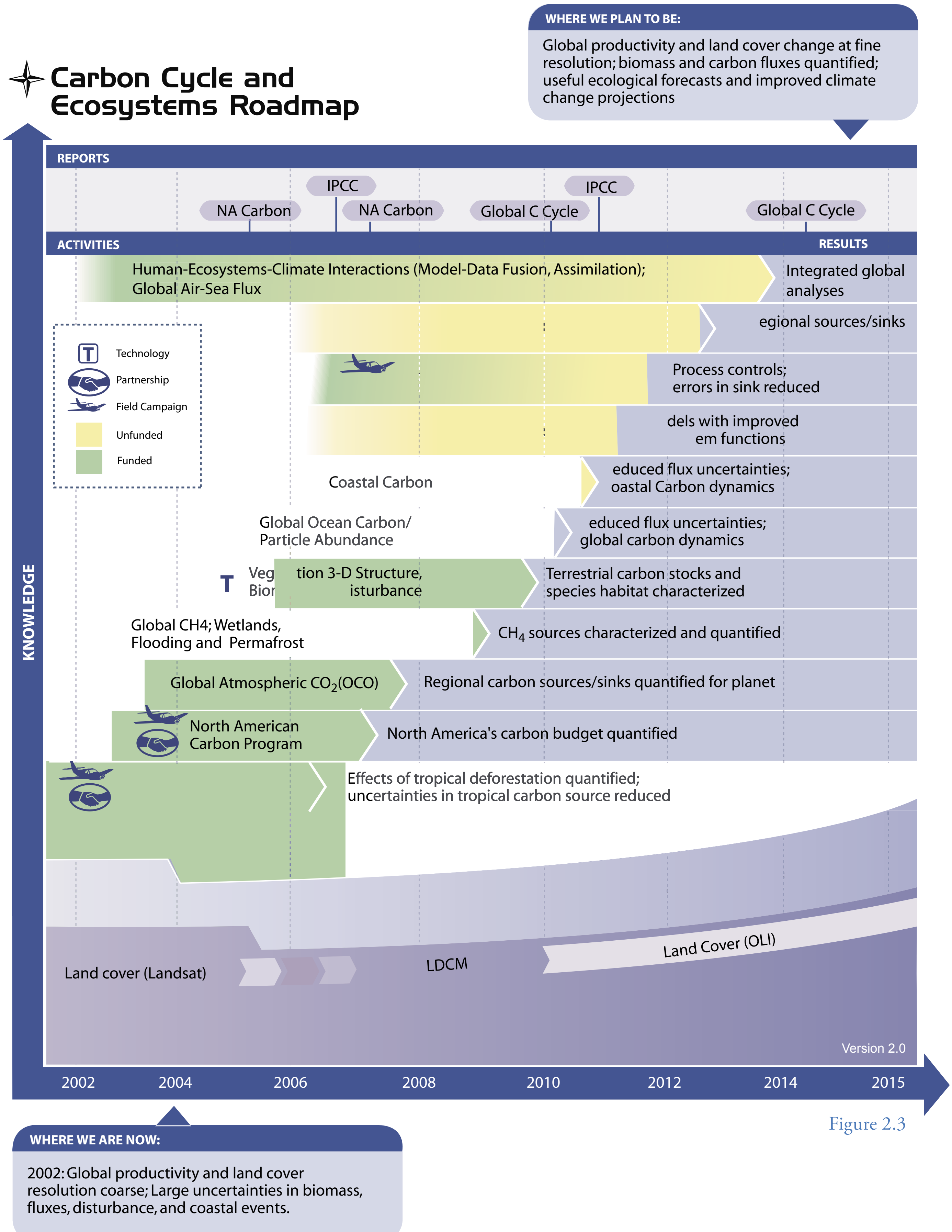
NASA expects to provide: the necessary monitoring and evaluation tools to assess the effects of climate change on ozone recovery and future atmospheric composition; improved climate forecasts based on our understanding of the forcings of global environmental change; and air quality forecasts that take into account the feedbacks between regional air quality and global climate change.

Research seeks to develop quantitative understanding of:

- Changes in atmospheric composition and the timescales over which they occur,
- Forcings (anthropogenic and natural) that drive the changes,
- Response of atmospheric trace constituents to global environmental change and the subsequent effects on global climate, and
- Effects of global atmospheric chemical and climate changes on regional air quality.

As depicted on the atmospheric composition roadmap (figure 2.2), achievements in these areas via advances in observations, data assimilation, and modeling enable improved predictive capabilities for describing how future changes in atmospheric composition affect ozone, climate, and air quality.

Drawing on global observations from space, augmented by suborbital and ground-based measurements, NASA is uniquely poised to address these issues. This integrated observational strategy is furthered via studies of atmospheric processes using unique sub-orbital platform-sensor combina-



Carbon Cycle and Ecosystems Roadmap
WHERE WE PLAN TO BE:
Global productivity and land cover change at fine resolution; biomass and carbon fluxes quantified; useful ecological forecasts and improved climate change projections
REPORTS
IPCC
NA Carbon
NA Carbon
Global C Cycle
IPCC
Global C Cycle
ACTIVITIES
RESULTS
Human-Ecosystems-Climate Interactions (Model-Data Fusion, Assimilation); Global Air-Sea Flux
Integrated global analyses
egional sources/sinks
Technology
Partnership
Field Campaign
Unfunded
Funded
Process controls; errors in sink reduced
dels with improved em functions
Coastal Carbon
educed flux uncertainties; oastal Carbon dynamics
Global Ocean Carbon/ Particle Abundance
educed flux uncertainties; global carbon dynamics
T
Veg Bior
tion 3-D Structure, isturbance
Terrestrial carbon stocks and species habitat characterized
Global CH4; Wetlands, Flooding and Permafrost
CH_4 sources characterized and quantified
Global Atmospheric CO_2(OCO)
Regional carbon sources/sinks quantified for planet
North American Carbon Program
North America's carbon budget quantified
Effects of tropical deforestation quantified; uncertainties in tropical carbon source reduced
Land cover (Landsat)
LDCM
Land Cover (OLI)
Version 2.0
KNOWLEDGE
2002
2004
2006
2008
2010
2012
2014
2015
WHERE WE ARE NOW:
2002: Global productivity and land cover resolution coarse; Large uncertainties in biomass, fluxes, disturbance, and coastal events.

Figure 2.3

tions to investigate, for example: (1) the processes responsible for the emission, uptake, transport, and chemical transformation of ozone and precursor molecules associated with its production in the troposphere and its destruction in the stratosphere; and (2) the formation, properties, and transport of aerosols in the Earth's troposphere and stratosphere. The research strategy in the atmospheric composition focus area encompasses an end-to-end approach for instrument design, data collection, analysis, interpretation, and prognostic studies.

Through the implementation of a robust program of research over the past two decades, we have made significant progress in our current level of understanding of the variability of, forcings on, responses to, and consequences of changes in atmospheric composition. However, many questions remain. For example, halogen chemistry is known to be largely responsible for stratospheric O_3 loss, but the roles of chemistry vs. dynamics remain to be precisely quantified. The connection between climate change and ozone chemistry has been recognized, but uncertainties remain regarding the effects on the timing and extent of ozone recovery. In the troposphere, we have observed varying trends in ozone; however its geographical evolution and trends remain to be quantified. Similarly, the spatial and temporal variations in the oxidizing capacity require further characterization. Global observations have shown transport of tropospheric ozone over large (hemispheric) distances. However, the extent to which regional pollution can be attributed to such long-range transport remains to be quantified. In the climate area, radiatively important changes in atmospheric water vapor have been observed, but these temporal variations are not quantitatively understood so that future changes can be predicted. Observational advances have yielded important information on the geographical and vertical distribution of atmospheric aerosols. Nevertheless significant further study is required before we can fully quantify aerosol evolution, composition, vertical distribution, and radiative impacts at a level where the information can be used in climate models.

2.1.3 Carbon Cycle and Ecosystems

Environmental change and human activities alter Earth's ecosystems and the biogeochemical cycles that are critical to the habitability of our planet. In addition to providing habitat and natural resources while nurturing crucial biodiversity, ecosystems interact with numerous geochemical and physical systems to maintain the global carbon cycle and its control over changes in atmospheric CO_2 and CH_4 and thus climate. Over the past two centuries, fossil fuel emissions and other human activities increased atmospheric CO_2 by 30% and CH_4 by 150% to concentrations unprecedented over the past 400,000 years. Discerning the response of the Earth system to these changes is fundamental to NASA's mission to understand and protect our home planet.

Ecosystems respond continuously to environmental variability and change as well as to numerous disturbances by human activities and natural events. Responses range from changes in ecosystem distribution and extent; impacts on natural resources (e.g., food, fiber, fuel, and pharmaceutical products); ecosystem services (e.g., cleaning of water and air, climate and weather regulation, carbon and nutrient storage and cycling, habitat, maintenance of water resources) to variations in fundamental processes including exchanges of energy, momentum, trace gases, and aerosols with the atmosphere that in turn influence climate.

Our ability to contend with these changes requires observations and fundamental understanding of the responses of ecosystem processes and dynamics to environmental change and to disturbance by human activities and natural events. We must assess the implications of these changes for food production, sustainable resource management, carbon management, conservation of biodiversity, and the maintenance of a healthy environment. In addressing these needs, the Carbon Cycle and Ecosystems Focus Area addresses the following science questions:

- How are global ecosystems changing?
- What changes are occurring in global land cover and land use, and what are their causes?
- How do ecosystems, land cover and biogeochemical cycles respond to and affect global environmental change?
- What are the consequences of land cover and land use change for human societies and the sustainability of ecosystems?
- What are the consequences of climate change and increased human activities for coastal regions?
- How will carbon cycle dynamics and terrestrial and marine ecosystems change in the future?

The Carbon Cycle and Ecosystems Roadmap (figure 2.3) summarizes NASA's strategy for using the global, synoptic perspective of remote sensing to document and understand changes in Earth's carbon cycle, land cover, and ecosystems.

The focus area addresses the distribution and cycling of carbon among the active land, ocean, and atmospheric reservoirs and ecosystems as they are affected by human activity, as they change due to their own intrinsic biogeochemical dynamics, and as they respond to climatic variations and, in turn, affect climate. The goals are to:

- Quantify global productivity, biomass, carbon fluxes, and changes in land cover;
- Document and understand how the global carbon cycle, terrestrial and marine ecosystems, and land cover and use are changing; and
- Provide useful projections of future changes in global carbon cycling and terrestrial and marine ecosystems for use in ecological forecasting and for improving climate change predictions.

Research focuses on providing data and information derived from space-based remote sensing systems to answer focus area science questions. In order to address the heterogeneity of living systems, frequent repeat observations at both moderate and high spatial resolutions are required. Complementary airborne and in situ observations, intensive field campaigns and related process studies, fundamental research, data and information systems, and modeling are all essential for interpreting satellite observations and providing answers to focus area science questions.

The ultimate goal is to project future conditions and trends for ecosystems and the global carbon cycle. This focus area contributes to the improvement of climate projections for 50–100 years into the future by providing key inputs for climate models, including future atmospheric CO_2 and CH_4 concentrations and representations of key ecosystem and carbon cycle process controls on the climate system. The outbreak and spread of harmful algal blooms, occurrence and spread of invasive exotic species, and the productivity of forest and agricultural systems exemplify ecological forecasts. Resource managers need such forecasts in order to warn the public, target the deployment of resources for mitigation or containment, plant different crops or employ alternative management practices. Policy makers need such forecasts to assess the impacts of various response options and plan for market responses and societal consequences.

Major challenges for the next decade are to document, quantify, and explain decadal-scale variability and trends in both aquatic and terrestrial primary productivity at kilometer spatial resolution, perform repeated high-resolution (~30 m) inventories of land cover and land use change, and report annual balanced global carbon budgets. To meet these challenges, we must characterize and quantify interannual variability, understand key controlling processes, and identify and quantify sources and sinks at sub-regional (~100 km) scales, both on land and within ocean margins. New insight about physiology (e.g., stress effects and efficiency of photosynthetic light use) and the ability to identify groups of species called "functional groups" with similar ecological functions (e.g., nitrogen fixing species, dimethyl-sulfide producers, invasive species) are critical to better understanding of primary productivity and carbon dynamics both on the land and in the ocean.

Well-calibrated and validated systematic observations of moderate-resolution ocean color, vegetation biophysical properties, fire, and land cover as well as high-resolution land cover comprise a critical foundation for focus area research. Major advances in knowledge require the new activities delineated on the roadmap (figure 2.3). The Large-Scale Biosphere Atmosphere Experiment in Amazonia (LBA) to understand the effects of tropical forest conversion, re-growth, and selective logging on carbon storage, nutrient dynamics, and trace gas fluxes is entering its final synthesis and integration phase. As LBA is completed, emphasis is shifting to the interagency North American Carbon Program (NACP) in order to quantify and explain North America's carbon balance. A new ESSP satellite mission to measure atmospheric CO_2 and advance our ability to quantify regional carbon sources and sinks is in the early stages of development.

New measurements of vegetation three-dimensional structure and high resolution atmospheric CO_2 profiles will be needed to quantify terrestrial carbon stocks and global sources and sinks, respectively, with sufficient accuracy to balance the global carbon budget and monitor carbon management (both sequestration and emissions reduction) activities. New information on vegetation structure also will enable the characterization of species habitats important for improved ecological forecasts. New measurements of carbon in the coastal ocean and of particle content or profiles throughout the ocean will be needed to reduce uncertainties in coastal carbon fluxes and to quantify carbon export to the deep ocean. In 5–10 years, an intensive Southern Ocean carbon program will be needed to resolve uncertainties in the size, dynamics, and global significance of the Southern Ocean as a carbon sink as well as the processes controlling this sink. In addition, new types of measurements will be needed to characterize plant physiological processes and identify plant functional groups in order to improve process characterizations in ecological models; the candidate measurement technologies (e.g., hyper-spectral, multi-spectral lidar) and analysis approaches will require study and development.

Throughout the next decade, research will be needed to advance our understanding of and ability to model human-ecosystem-climate interactions so that an integrated understanding of Earth system function can be applied to our goals. Changes in social, economic, and cultural systems are combining with global environmental changes as forcings of change in a world that is more populated, urban, and interconnected than ever before. Innovative research to blend social and natural science information and to advance model coupling, model-data fusion, and data assimilation approaches will be needed.

NASA research in the Carbon Cycle and Ecosystems Focus Area will employ the global, synoptic perspective of space and unique NASA scientific and management expertise to reduce uncertainties and provide quantitative information concerning atmospheric concentrations of greenhouse gases, changes in terrestrial ecosystem and oceanic carbon sinks, trends in primary productivity, species extinction and invasion, land cover and land use change, and the health and sustainability of global ecosystems. Continuing NASA research will focus on tracking, comprehending, and predicting these changes and their impacts on society and the Earth system. Specifically this program of research will produce:

- Assessments of ecosystem response to climatic and other environmental changes and the effects on food, fiber, biodiversity, primary productivity, and other ecological goods and services;
- Quantitative carbon budgets for key ecosystems along with the identification of sources and sinks of carbon dioxide and other greenhouse gases;
- Documentation and prediction of land cover and land use change as well as assessments of consequences to society and for resource sustainability;
- Understanding of ecosystem interactions with the atmosphere and hydrosphere leading to comprehensive modeling of the exchange of gases, aerosols, water, and energy among the components of the Earth system;
- Better representations of ecosystem processes within global climate models leading to more credible climate predictions.

The resulting information and scientific understanding will enable sound resource management strategies and policy decisions pertaining to carbon, agriculture, forestry, fisheries, and other natural resources.

2.1.4 Water and Energy Cycle

The availability of fresh water on planet Earth affects billions of people. Floods and drought can be life-threatening. The following questions guide research within the Water and Energy Cycle Focus Area:

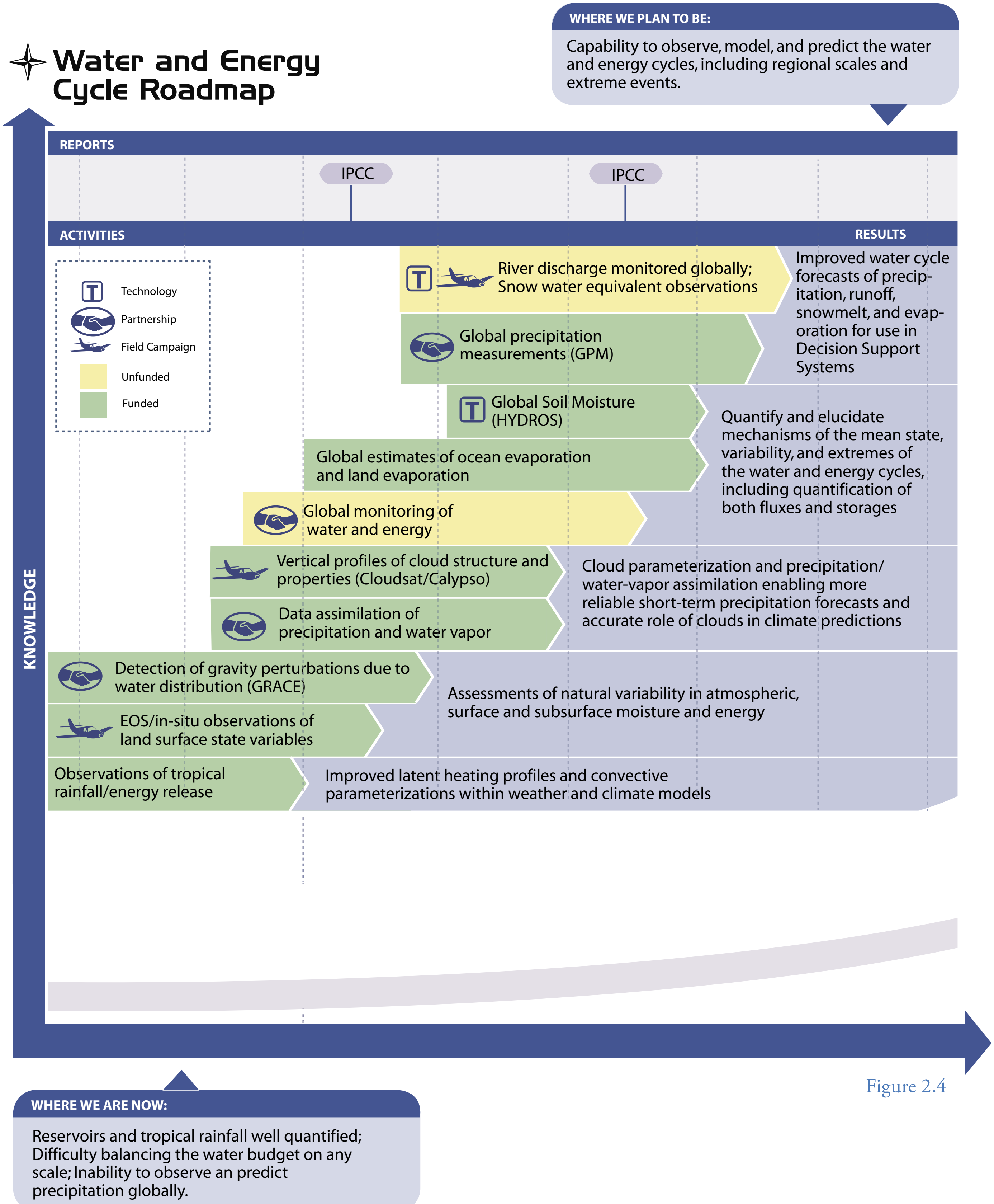
- How are global precipitation, evaporation, and the cycling of water changing?
- What are the effects of clouds and surface hydrologic processes on Earth's climate?
- How are variations in local weather, precipitation and water resources related to global climate variation?
- How will water cycle dynamics change in the future?

As these water and energy cycle questions are addressed, we gain the understanding and observing capabilities to better contend with the hydrologic, water resource, and related weather issues that underlie habitability of the planet.

The Water and Energy Cycle Focus Area studies the distribution, transport, and transformation of water and energy within the Earth system. Since solar energy drives water and energy exchanges, the energy cycle and the water cycle are intimately entwined. Thus, research focuses on the closely linked budgets of energy and moisture. Focus area research is aligned with national and international programs including the Global Energy and Water Cycle Experiment and the water cycle activities of the U.S. Climate Change Science Program.

The overarching, long-term goal of the Water and Energy Cycle Focus Area is to develop capabilities to observe, model, and predict the water and energy cycles, including phenomena at regional scales and extreme events such as drought and floods. This goal requires an accounting of the key reservoirs and fluxes within the global water and energy cycles, including their spatial and temporal variability, through integration of all necessary observations and research tools. Further, this goal requires not only documenting and predicting trends in the rate of the Earth's water and energy cycling, but also changes in the frequency and intensity of related meteorological and hydrologic events.

The approach to these goals rests on a combination of observations, understanding, modeling, prediction, and decision-support systems presented in the Water and Energy Cycle Roadmap (figure 2.4). This integrated approach will yield improved overall knowledge and improved predictions of the changing of the water and energy cycles. Future mis-



Water and Energy Cycle Roadmap
WHERE WE PLAN TO BE:
Capability to observe, model, and predict the water and energy cycles, including regional scales and extreme events.
REPORTS
IPCC
IPCC
ACTIVITIES
RESULTS
Technology
Partnership
Field Campaign
Unfunded
Funded
River discharge monitored globally; Snow water equivalent observations
Global precipitation measurements (GPM)
Improved water cycle forecasts of precip-itation, runoff, snowmelt, and evap-oration for use in Decision Support Systems
Global Soil Moisture (HYDROS)
Global estimates of ocean evaporation and land evaporation
Global monitoring of water and energy
Quantify and elucidate mechanisms of the mean state, variability, and extremes of the water and energy cycles, including quantification of both fluxes and storages
Vertical profiles of cloud structure and properties (Cloudsat/Calypso)
Data assimilation of precipitation and water vapor
Cloud parameterization and precipitation/ water-vapor assimilation enabling more reliable short-term precipitation forecasts and accurate role of clouds in climate predictions
Detection of gravity perturbations due to water distribution (GRACE)
EOS/in-situ observations of land surface state variables
Assessments of natural variability in atmospheric, surface and subsurface moisture and energy
Observations of tropical rainfall/energy release
Improved latent heating profiles and convective parameterizations within weather and climate models
KNOWLEDGE
WHERE WE ARE NOW:
Reservoirs and tropical rainfall well quantified; Difficulty balancing the water budget on any scale; Inability to observe an predict precipitation globally.

Figure 2.4

sions on the roadmap will provide key measurements for this focus area including: soil moisture, ocean water storage and flux, global precipitation, ground-water storage, tropospheric water storage, and atmospheric water and energy storage.

Precipitation has only recently been measured from space by the Tropical Rainfall Measuring Mission (GPM). The Global Precipitation Measurement mission will extend remote sensing of precipitation globally, allowing estimation of this input term in Earth's water budget. Evaporation cannot be measured directly, but can be estimated using models based on estimates of the amount of radiation absorbed by the land, oceans, and atmosphere and validated using selected satellite measurements including ocean salinity from Aquarius and soil moisture from HYDROS. The Water and Energy Cycle Focus Area concentrates on storage as soil moisture, ground water, surface water, and snow.

Other missions whose primary measurements address the needs of other focus areas will provide inputs on sea ice, atmospheric water content, land use and land cover, and total ocean water content. Simultaneous measurements over a two- to three-year period are critical to balancing the water and energy budgets. Measurements of soil moisture with two- to three-day frequency set the highest required temporal resolution within the budgets.

Algorithms for future sensors that can provide better spatial and temporal resolution and coverage are developed through airborne and in situ campaigns and a robust research and analysis program. In situ measurements are used to validate spaceborne measurements and model results. Future measurements, high-resolution soil moisture measurements on a global scale, surface water in rivers and lakes, and snow water equivalent will require some new technologies to be developed, in larger apertures for both passive and active microwave instruments. Higher resolution soil moisture measurements on a global scale will also require improved downlink capabilities.

Water and energy cycle modeling requires projections of future changes in surface hydrological parameters (soil moisture, runoff, evapotranspiration) due to changes in land use and land cover as well as enhancements to radiative transfer models to support finer details of atmospheric interactions.

Water and energy cycle research activities should augment and help connect the goals of the Weather Focus Area, where fast processes are studied, and the Climate Variability and Change Focus Area, where longer term process are studied. To achieve the desired accuracy in characterizing the water budget requires several key climatic inputs including sea-ice extent, as well as atmospheric water content at all levels. The energy budget requires significant inputs on solar radiation and Earth radiation.

By 2015, research within the Water and Energy Cycle Focus Area is expected to improve intermediate range forecasts for droughts and seasonal water supply and predict global scale energy storage and transport in the atmosphere by meeting two goals:

- Enable seasonal precipitation forecasts with greater than 75% accuracy at 10's of km resolution; and
- Balance global water and energy budgets.

2.1.5 Weather

Weather has enormous influence on human activities. Favorable weather is in many cases critical for agricultural productivity while severe weather can disrupt virtually every enterprise and endanger human life, property, and natural resources. Accurate weather prediction allows preparation for severe events and adaptation to day-to-day variations. Accurate hurricane predictions as well as tornado tracking save lives and property. Agriculture, transportation systems, and numerous other endeavors all rely on weather forecasts for daily decisions and resource allocation. NASA and NOAA have collaborated for decades to enable NOAA to exploit new NASA observing capabilities and research to improve NOAA's operational environmental satellites and weather forecasting models.

The direct question:

> How can weather forecast duration and reliability be improved?

guides research within NASA's Weather Focus Area.

The Weather Focus Area seeks to apply NASA remote sensing expertise to obtain accurate and globally-distributed measurements of the atmosphere for assimilation into operational weather forecast models thereby improving and extending weather predictions. As shown in the weather roadmap (figure 2.5) developed in collaboration with the U.S. Weather Research Program, a primary component of NASA's effort is directed toward resolving challenging problems such as how to use remote sensing spectral data in the presence of some cloudiness and yet still achieve temperature and moisture soundings of quality similar to that obtained by instruments lofted by weather balloons.

Weather Roadmap

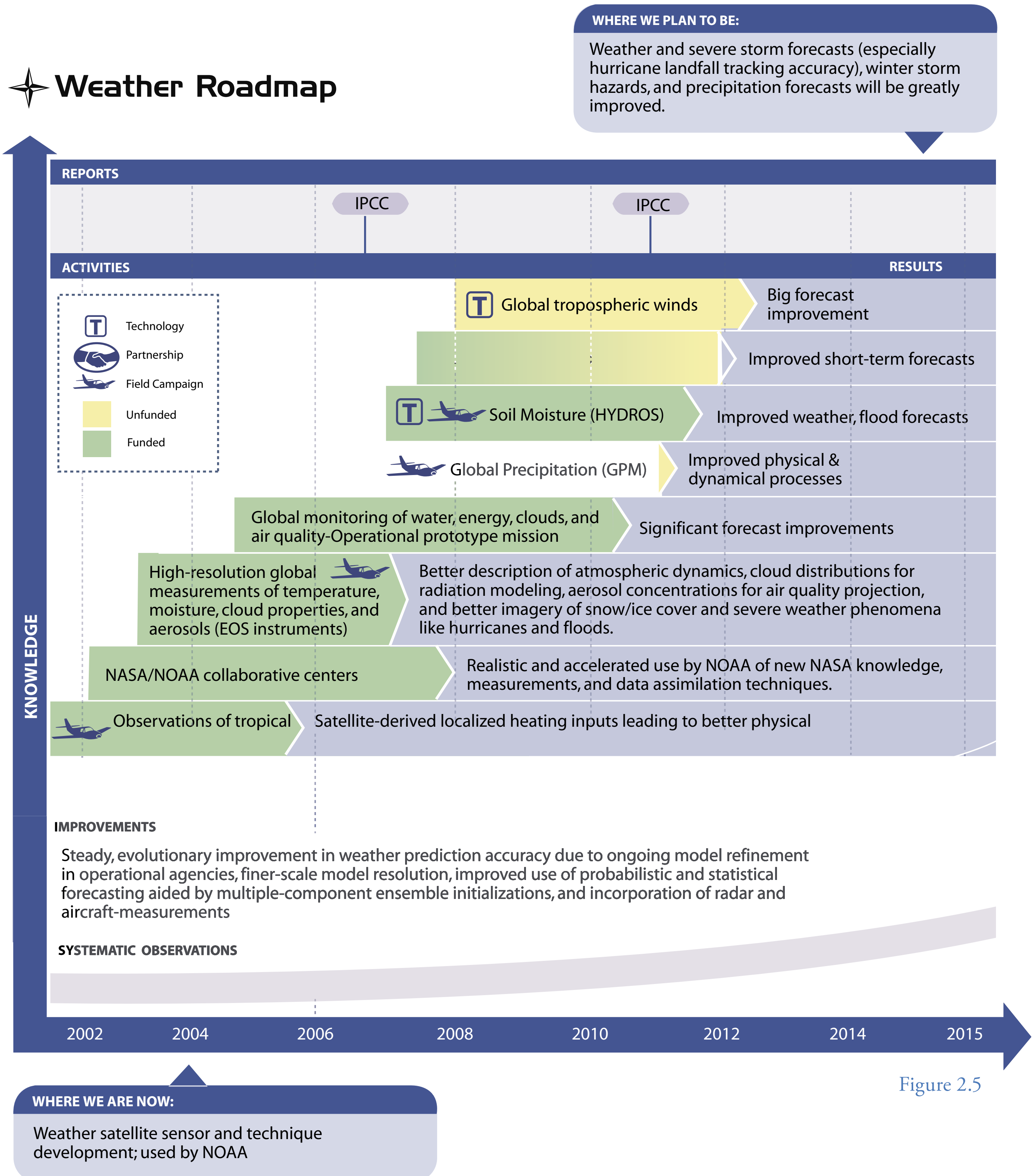


Figure 2.5

Accurate local and regional predictions begin with global simulations. These simulations require the assimilation of satellite measurements of the atmosphere in depth for the entire globe. NASA develops the satellite sensors for sounding the atmosphere's temperature and humidity structure. The latest high-accuracy sensor is the AIRS instrument on board the Aqua satellite. AIRS data are being studied intensely for inclusion into operational processing streams.

Currently, high priority is assigned to the detection and quantification of rainfall rate, generally measured by microwave remote sensing. Surface radars have long been able to estimate rainfall rate, with the assumption of appropriate drop-size distributions and a national network of Doppler radars estimate the locations of wind velocity couplets that signal likely tornado formation. NASA's first weather radar in space, TRMM, enabled global rainfall mapping throughout the seasons increased our understanding of storm-cloud characteristics accompanying various forms and levels of rainfall rates. Extension of satellite weather radar to a global constellation of active and passive sensors can pave the way for future operational missions.

Other NASA weather research is important for the design of new satellite sensors for cloud and rainfall characteristic measurement and focused field programs help researchers to understand the natural variability and structure of the atmosphere, clouds, and storms on finer and finer scales as the numerical models are able to handle the higher-resolution data.

Another key component of the current Weather Focus Area is a set of core efforts to assimilate new NASA satellite data into numerical forecast models and to assess the amount of forecast improvement. Two groups are currently working on this problem, the NASA/NOAA/USAF Joint Center for Satellite Data Assimilation and NASA's Short-term Prediction Research and Transition Center. These centers allow studies of the most effective ways of assimilating new satellite data into global and regional numerical models.

NASA's Earth Observing System provides an array of data for weather research including land and sea surface temperatures, could characteristics, bidirectional reflectance for interpreting air pollution concentrations, surface wetness, and polar winds. Not all of these measurements are currently being assimilated into numerical forecast models to determine their potential forecast impacts. As basic research concerning scales of variability and physical relationships to other parts of the Earth System is completed, additional EOS data products will be tested by NASA and NOAA for forecast improvement potential.

In addition to precipitation measurement, important new satellite missions to advance weather forecast accuracy include an operational surface moisture monitor, geostationary monitoring of lightning location, strength, and rate, and the global monitoring of vector wind fields through out the depth of the atmosphere. Perhaps the greatest value for a future satellite sensor to would be the implementation of a fleet of Doppler lidar sensors to measure global winds as a function of height.

2.1.6 Earth Surface and Interior

The Earth Surface and Interior Focus Area promotes the development and application of remote sensing to address the questions:

- How is the Earth's surface being transformed by naturally occurring tectonic and climatic processes?
- What are the motions of the Earth's interior, and how do they directly impact our environment?
- How can our knowledge of earth surface change be used to predict and mitigate natural hazards?

The overarching goal of the focus area is to assess, mitigate and forecast natural hazards that affect society, including such phenomena as earthquakes, landslides, coastal and interior erosion, floods and volcanic eruptions. The path to prediction includes comprehensively recording and understanding the variability of surface changes controlled by two types of forces: external such as climate; and the internal forces that are in turn driven by the dynamics of the Earth's interior. In order to produce a predictive capability, these observations of the Earth's transformation, must be modeled, interpreted, and understood. The advent of spaceborne sensing is vital to forecasting in the solid Earth sciences, providing a truly comprehensive perspective for monitoring the entire solid Earth system. NASA's principal partners in this focus area are the U.S. Geological Survey, the National Geospatial-Intelligence Agency (formerly NIMA), and the National Science Foundation.

Remote sensing empowers scientists to measure and understand subtle changes that reflect the response of the Earth to both the internal forces that lead to volcanic eruptions, earthquakes, landslides, and sea-level change as well as the climatic forces that sculpt the Earth's surface. A key observational

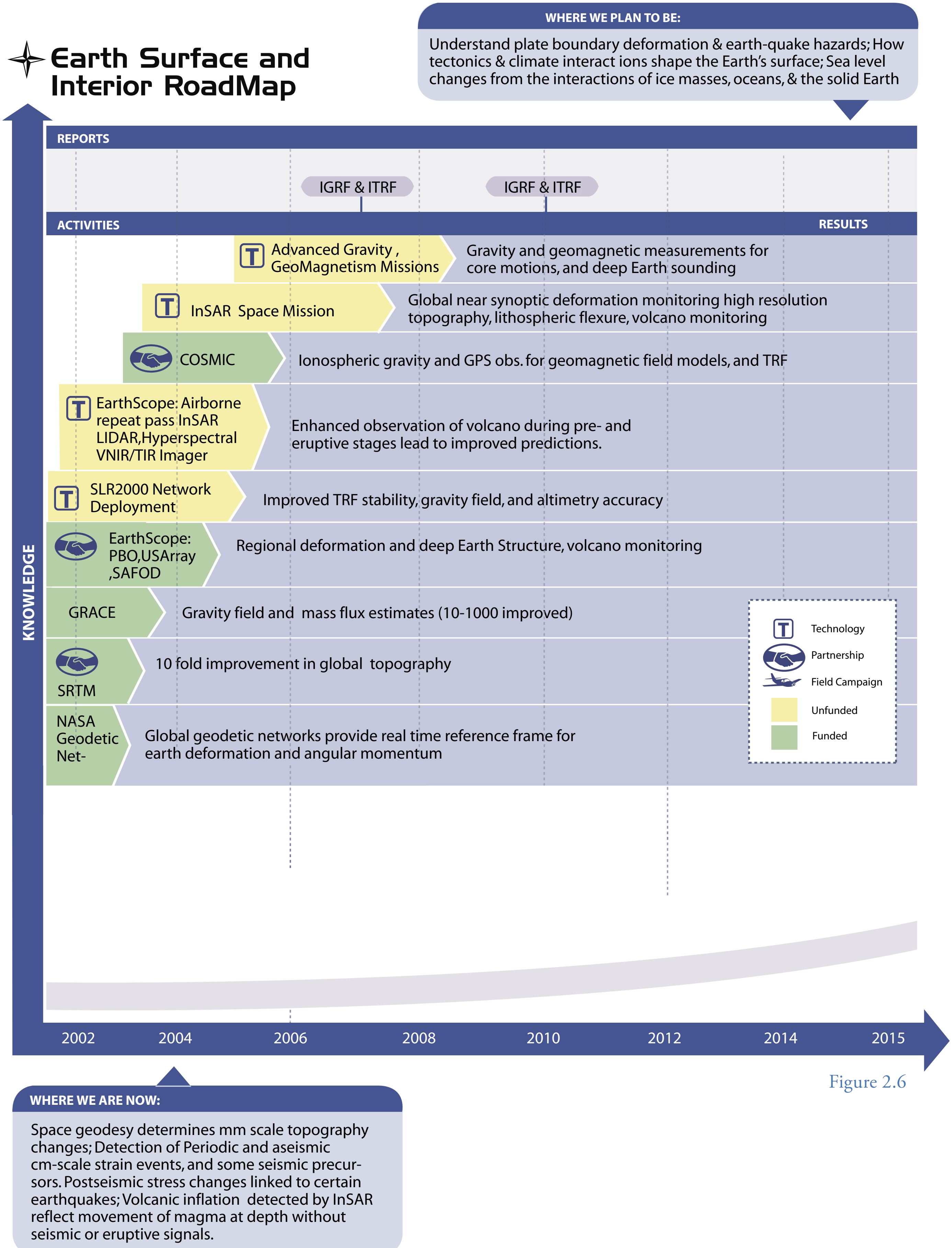

Earth Surface and Interior RoadMap
WHERE WE PLAN TO BE:
Understand plate boundary deformation & earth-quake hazards; How tectonics & climate interact ions shape the Earth's surface; Sea level changes from the interactions of ice masses, oceans, & the solid Earth
REPORTS
IGRF & ITRF
IGRF & ITRF
ACTIVITIES
RESULTS
Advanced Gravity , GeoMagnetism Missions
Gravity and geomagnetic measurements for core motions, and deep Earth sounding
InSAR Space Mission
Global near synoptic deformation monitoring high resolution topography, lithospheric flexure, volcano monitoring
COSMIC
Ionospheric gravity and GPS obs. for geomagnetic field models, and TRF
EarthScope: Airborne repeat pass InSAR LIDAR,Hyperspectral VNIR/TIR Imager
Enhanced observation of volcano during pre- and eruptive stages lead to improved predictions.
SLR2000 Network Deployment
Improved TRF stability, gravity field, and altimetry accuracy
EarthScope: PBO,USArray ,SAFOD
Regional deformation and deep Earth Structure, volcano monitoring
GRACE
Gravity field and mass flux estimates (10-1000 improved)
SRTM
10 fold improvement in global topography
NASA Geodetic Net-
Global geodetic networks provide real time reference frame for earth deformation and angular momentum
Technology
Partnership
Field Campaign
Unfunded
Funded
KNOWLEDGE
2002
2004
2006
2008
2010
2012
2014
2015
WHERE WE ARE NOW:
Space geodesy determines mm scale topography changes; Detection of Periodic and aseismic cm-scale strain events, and some seismic precursors. Postseismic stress changes linked to certain earthquakes; Volcanic inflation detected by InSAR reflect movement of magma at depth without seismic or eruptive signals.

Figure 2.6

strategy is to move towards geodetic and thermal imaging of the precise metrology of Earth's surface and its changes through lidar, radar constellations, and optical arrays. Such imaging coupled with geopotential field measurements will play a primary role in understanding the dynamics of the Earth's surface and interior.

The development of a stable terrestrial reference frame to better than a millimeter per year, the realization of topography and topographic change to sub-meter precision, and an understanding of changes in the Earth's angular momentum and gravity field are critical to accomplishing focus area goals. These data products provide accurate measures of changes in the Earth, including sea-level change, polar mass balance, and land subsidence. Optical and geodetic imaging using radar and lidar define the land surface to sub-meter precision to search for precursory events and to understand the Earth's surface response to both the fluid envelope and interior forces.

The Earth Surface and Interior Roadmap (figure 2.6) summarizes the elements of focus area research directed at the critical challenges of understanding the dynamics of Earth's surface and interior as a basis for predicting the occurrence of natural hazards.

The rate of sea-level change is estimated to be 1–2 mm/yr measured within the terrestrial reference frame. A critical component of these estimates is the response of the solid Earth, including subsidence and erosion in coastal zones and warping of the crust beneath the deepening oceans and thinning ice sheets. Gravity and magnetism are observables not only for the inner dynamics of the Earth but also for understanding the ionosphere, which responds to changes in the Earth's surface such as seismic waves and tsunamis, and can be used as proxies for surface motions, leading to space-based seismic imaging.

Near-term predictions of volcanic eruptions are moderately successful for certain limited and well-studied volcanic areas. These near-term predictions can be improved through better remote sensing, in particular optical and geodetic imaging coupled with enhanced computational modeling. Substantial challenges remain in modeling debris flow and long-term eruption prediction, which have a significant impact on development in volcanic regions and the global impact of mega-eruptions. Earthquake forecasting requires accurate modeling of fault interactions, which at its heart means understanding the state of stress in the crust and the strength of the lithosphere. Space geodesy is now beginning to give us a glimpse of precursory events, and the integration of geodetic and seismic models is leading to better estimates of crustal strength and dynamics in seismic zones. Visible, infrared and electromagnetic measurements are being studied for evidence of precursory phenomena and a better understanding of the physics of the earthquake cycle.

Modeling, calibration, and validation are essential components in the development of accurate forecasting capabilities. The Earth Surface and Interior Focus Area views natural laboratories as a critical component for the validation and verification of remote sensing algorithms. NASA joins with NSF and USGS in support of the EarthScope initiative to apply modern observational, analytical, and telecommunications technologies to investigate the structure and evolution of the North American continent and the physical processes controlling earthquakes and volcanic eruptions. Other natural laboratories, such as the Asian Pacific Arc and Tien Shan-Caucasus studies of convergent plate boundaries for volcanic and earthquake hazards, are under development in conjunction with international partners. The International Solid Earth Research Virtual Observatory (iSERVO) will link advanced computational resources with distributed databases developed in part from natural laboratories and NASA's remote sensing systems. The objective of iSERVO is accurate forecasting of natural hazards through the implementation of an integrated strategy of observation and computational modeling.

2.2 Observations

NASA brings unique observations from space to bear on a broad range of Earth science problems and issues, expanding our understanding of Earth system dynamics and processes while informing environmental, natural resource, and societal planning and decisions. Satellite remote sensing is the only practical means of obtaining systematic measurements over the entire Earth surface for long time periods, and many applications have come to rely on this unique resource. Satellite remote sensing is critical for extending in situ terrestrial, oceanic, and atmospheric measurements through time and over large regions. Through the continuing development of new sensors, platforms, and data products for Earth observation from space as well as the calibration, validation, and interpretation of satellite observations and their assimilation into Earth system models, NASA makes essential contributions to Earth science, observation, and monitoring.

The intellectual capital for Earth observations is vested in a robust research program. As new ideas and understanding emerge, research generates innovative observing techniques and processing algorithms, conducts field tests, and generally charts the path for scientific and engineering developments that enable improved Earth observations. The science questions and issues that guide research within NASA's six Earth science focus areas (table 2.1) dictate broad observation requirements, and those needs with sufficient priority are incorporated into focus area roadmaps. Research addressing specific science questions sharpens requirements, in some cases identifying well-defined sensor and platform options—research projects may be focused on sensor development as a primary topic. The development of algorithms for processing remote sensing measurements into data products is a primary NASA focus in Earth science research.

To be fully successful, NASA's research in Earth observation requires close partnerships with those designing, developing, and producing remote sensing technology and satellite systems, organizations that undertake long-term monitoring by remote sensing, and national and international partners with similar interests, requirements, and missions.

2.2.1 Research and Development for Earth Observation Technology

NASA's Earth Science Technology Office (ESTO) coordinates, integrates, and manages the development of advanced technologies for use in future Earth system measurements. ESTO initiatives engage scientists and engineers from NASA centers and other government laboratories, industry, and academic institutions in technological development, risk reduction, and readiness for space missions. This effort includes not only new sensors but also the data retrieval, distribution, and processing capabilities to incorporate remote sensing measurements from space into data products for Earth science research, monitoring, and a host of applications. A companion NASA Earth Science Technology Plan (figure 1.2) describes ESTO development activities to meet the observation goals of the focus areas as expressed in their research roadmaps.

Two programs organize ESTO work on observation technologies. The Advanced Component Technologies Program implements a broad effort in technology develop for observing system components while the Instrument Incubator Program develops more mature instrument and measurement technologies that are ready for initial testing including deployment in suborbital laboratories, on balloons, or in airplanes. Similarly, the Advanced Information System Technologies program develops advanced capabilities for collecting, transmitting, processing, disseminating, and archiving information about the Earth system.

2.2.2 Satellite Missions

Since its inception, NASA has exploited satellite platforms to observe the Earth, providing a critical resource for Earth science research. As a result of growing research efforts, many measurements from space are now routine and essential. For example, satellite remote sensing has become indispensable for accurate weather forecasts and severe storm warnings. But other important measurements require new concepts that take advantage of advancing technology—many observations remain difficult to interpret. Earth science research drives NASA satellite missions, and the focus area roadmaps indicate major requirements for developing or extending satellite remote sensing.

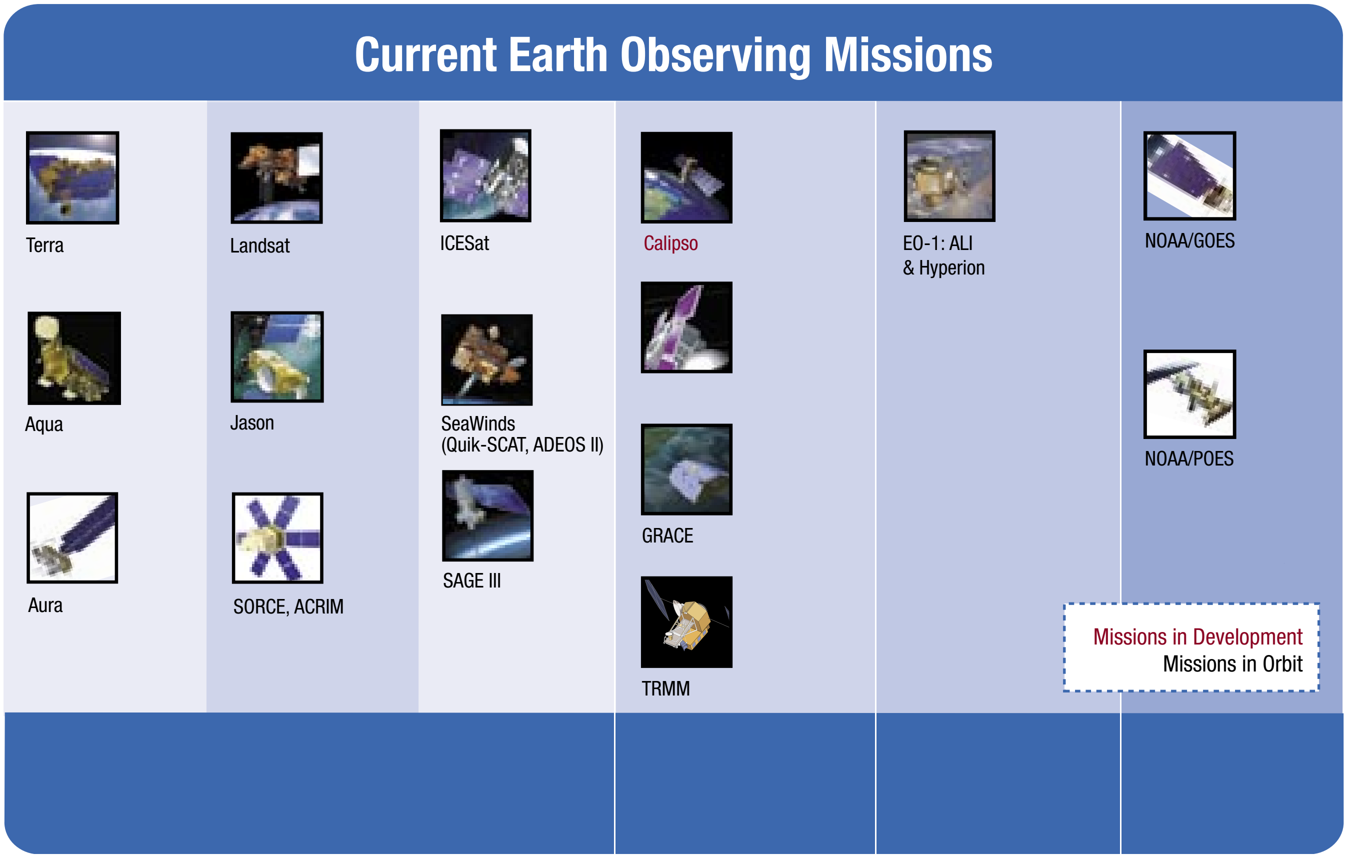
From the 1960's through the 1980's, NASA and its partners steadily advanced capabilities to observe the Earth, launching a new era of scientific discovery by remote sensing from space. Key early results include discovery of the processes behind Antarctic ozone depletion; the Earth's response to incoming solar radiation; and the extent, causes, and impacts of land use and land cover change. The emerging view of the whole Earth enabled by satellite perspectives stimulated the development of an interdisciplinary Earth system science motivated to observe a sufficient suite of characteristics and variables to identify and track change over long time periods at scales from local to global.

Beginning with the launch of the Terra satellite in December 1999, NASA began to deploy an Earth Observing System (EOS) with the objective of collecting systematic, well-calibrated and validated, long-term measurements to characterize and detect change in the Earth system (figure 2.7). A suite of polar-orbiting and low-inclination satellites, each carrying multiple sensors, linked to a data system for acquisition, processing, and distribution, provides numerous science data products with global coverage and repeated measurements of sufficient frequency and accuracy to detect change.

With the launch of Aura in July 2004, NASA completed the deployment of the first phase of the observing system that now provides a core set of data products to characterize the Earth system and to identify and track changes.

EOS data provide a foundation for Earth science research within NASA, and continuing many EOS measurements is now recognized as important not only for attaining research goals but for meeting critical decision and management needs as well. Many research activities and goals of the science focus areas hinge on EOS data products, and the focus area roadmaps show the dependence of specific research directions and goals on EOS measurements. A companion plan for Earth

Figure 2.7



Science Applications describes the use of EOS data within decision-support systems for an array of National application areas.

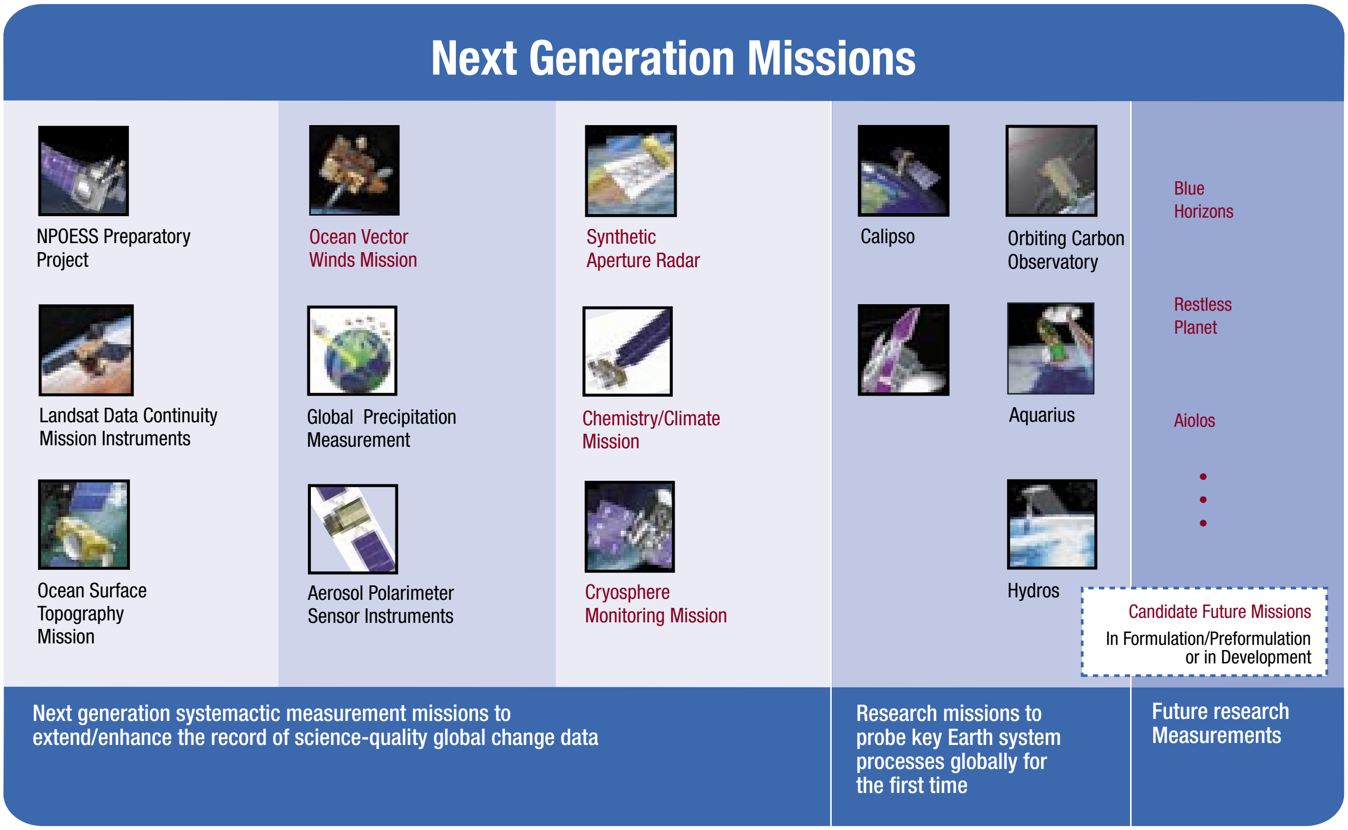
NASA, other U.S. federal and state agencies, as well as organizations in other countries support a host of research projects using EOS data. In addition to addressing scientific issues and questions, many of these efforts seek to extend Earth observing capabilities by developing improved or new data products or through new satellite missions. Research using EOS data ranges from highly-focused, single-investigator studies to large interdisciplinary programs. Investigators are making increasing use of data from multiple sensors and platforms, taking advantage of the coordinated measurements of the EOS. Formation flying by the Aqua, CALIPSO, CloudSat, Parasol, and Aura spacecraft opens new opportunities for targeted measurements in which a sensor on one platform is adjusted based on observations acquired by a sensor on a platform flying ahead in the formation.

Research is just beginning to take full advantage of the EOS. But even as unprecedented EOS data are processed and analyzed, exploratory missions continue to develop innovative observational capabilities from space that probe poorly understood processes or demonstrate new technologies (figure 2.8). The Earth System Science Pathfinder program is the primary source of exploratory missions to complement the EOS. Competitively selected Pathfinder missions address specific research questions and are developed and implemented on an aggressive schedule. Principal investigators lead Pathfinder missions from development through data distribution.

As these programs compliment and extend the Earth Observing System (figure 2.8), the domain of Earth observations from space is constantly extended.

Satellite observations are now enabling increasingly interdisciplinary Earth science research leading to better understanding of the Earth as a system that responds as a whole to forces acting on its major components. Earth system models are incorporating data from multiple sensors as constraints on model parameters and solutions. For example, measurements of atmospheric CO_2 by the Orbiting Carbon Observatory, a Pathfinder mission, coupled with observations of vegetation

Figure 2.8



phenology by the MODIS sensors provide far better understanding of seasonal variations in carbon sources and sinks on land.

2.2.3 Suborbital and Surface Observations

Measurements on land and within the Earth's atmosphere and oceans are required to calibrate and validate measurements from space and are an integral part of a complete Earth observing system. Suborbital measurements and sensors on the Earth's surface augment observations from space with higher spatial and temporal resolutions that can be targeted at specific regions or focused on specific processes. Additionally, major experiments and field campaigns provide detailed information about and understanding of systems and processes observed from space. Thus, NASA recognizes that a comprehensive Earth observing system requires a global, integrated approach combining observations from spacecraft, suborbital vehicles such as aircraft and balloons, surface instruments such as carbon flux towers and ocean buoys, as well as major experiments and field campaigns engaging multiple surface and suborbital measurements carefully coordinated with satellite observations.

Aircraft and other suborbital platforms provide laboratories for testing new approaches and sensors. Experience with suborbital observations is important for determining the value of sensors for space missions. Data collected by prototype sensors or simulators for sensors intended for satellite deployment are crucial for algorithm development and testing. In addition to their critical role in calibration, validation, and sensor development, suborbital remote sensing data compliment satellite observations with higher resolutions and less interference that are often critical for characterizing heterogeneity in space or time or for understanding complex processes.

In order to characterize Earth system dynamics and understand the processes involved, NASA undertakes selected field campaigns and experiments to collect more detailed data that can be related to satellite and suborbital observations. Such field data provide insights about system interactions and feedbacks. Understanding and quantifying these phenomena enables the development of more robust algorithms for remote sensing products beyond those closely related to the measurements collected in space.

Suborbital science within NASA is evolving from an enabling function for sensor testing and supportive observations to serve as an essential means of observing local and regional phenomena within global satellite observations.

2.2.4 Systematic Earth Observing Systems and Data Records

The U.S. Climate Change Science Program (CCSP) is developing and deploying a global, integrated, and sustained observing system to address science requirements and decision support needs at appropriate accuracies and spatial and temporal resolutions. Within this effort, CCSP seeks to address the overarching question:

> How can we provide active stewardship for an observation system that will document the evolving state of the climate system, allow for improved understanding of its changes, and contribute to improved predictive capability for society?

NASA develops critical space-based observations to meet this challenging goal and leads research to utilize Earth observations to understand the Earth system and to predict change. Currently, EOS sensors (figure 2.7) are providing unprecedented measurements of Earth system properties and variables with global coverage. The challenge for the next decade is to maintain current capabilities, implement new elements, make operational the elements that need to be sustained, and integrate observations into a comprehensive global system. The CCSP envisions an observing system that addresses research and decision support needs in climate, the global biogeochemical cycles of carbon and other elements, water, energy, atmospheric composition, and changes in land cover and land use. The goals of NASA's Earth science focus areas intentionally span the breadth of this ambitious CCSP observing system.

In the decades ahead, NASA research and Earth remote sensing missions will extend substantially our capabilities for Earth observations from space. As measurements become reliable and well understood, they will be incorporated into a growing suite of systematic observations obtained operationally. In most instances, an agency other than NASA with appropriate responsibility will undertake operational measurements and monitoring, taking advantage of and sustaining the capabilities of NASA research missions. Frequently, NASA is a partner in the development and operation of these missions.

Sustained measurements are meant to identify and monitor long-term changes in the Earth system. Such Earth system data records must meet standards that allow comparison of measurements over extended periods, frequently through the lifetimes of multiple platforms and sensors, while maintaining sufficient and well-understood accuracy. The CCSP refers to such data records as "climate quality," meaning that the records are suitable for investigating change over time periods corresponding to climatic variations and change. Achieving the necessary consistency and accuracy requires observations that conform uniformly to underlying principles. As summarized in table 2.3, the Global Climate Observing System (GCOS) specifies a core set of principles adopted by the CCSP for Earth system data records.

The GCOS principles highlight the importance of radiance calibration, calibration monitoring, and satellite-to-satellite cross-calibration. Table 2.2 summarizes additional principles for satellite systems acquiring Earth system data records.

Within NASA, the Earth science focus areas give particular attention to developing and maintaining Earth system data records. To insure integration and provide planning for the transition of research observing systems into long-term operational monitoring, focus areas designate measurement teams charged with suites of Earth system data records, and the focus area roadmaps show the transition of systematic observations into operational status. A prominent example is the incorporation of many EOS measurements into the National Polar-orbiting Operational Environmental Satellite System (NPOESS) to be operated by the Departments of Defense and Commerce in partnership with NASA.

Shorter term exploratory observations carried out with satellites, aircraft, ships, buoys, process-oriented field campaigns, and other finite duration research observations are all critical to successful deployment of satellite missions to retrieve Earth system data records. Satellite missions that bridge research systems to operational observing systems provide continuity in critical measurements, test sensor systems, and allow critical development of algorithms as well as calibration and validation schemes. The NPOESS Preparatory Project, which will continue selected EOS observations into the NPOESS era, provides the continuity not only in measurements but in algorithm development, calibration, and validation as well that is critical to obtaining Earth system data records.

2.3 Modeling, Analysis, and Prediction

A primary goal of Earth observations is to inform environmental predictions. These include climate change and its impacts; changes in atmospheric composition or in terrestrial and marine ecosystems; phenomena such as changes in ocean

Table 2.2

GCOS principles for satellite observations to acquire Earth system data records.
1. Constant sampling within the diurnal cycle, minimizing the effects of orbital decay and orbit drift, should be maintained.
2. A suitable period of overlap for new and old satellite systems should be ensured for a period adequate to determine inter-satellite biases and maintain the homogeneity and consistency of time-series observations.
3. Continuity of satellite measurements through appropriate launch and orbital strategies should be ensured.
4. Rigorous pre-launch instrument characterization and calibration, including radiance confirmation against an international radiance scale provided by a national metrology institute, should be insured.
5. On-bo
6. Operational
7. Data systems needed to facilitate user access to climate products, metadata, and raw data, including key data for delayed-mode analysis, should be established and maintained.
8. Use of functioning baseline instruments that meet the calibration and stability requirements stated above should be maintained for as long as possible, even when these exist on de-commissioned satellites.
9. Complementar
10. Random errors and time-dependent biases in satellite observations and derived products should be identified.

circulation or El Niño events that contribute to climate variability; weather; or earthquake risk. Thus, improvements in model accuracies for predictions are an important aspect of NASA Earth science research, and prediction is a cornerstone of research within each science focus area.

Modeling and analysis are a key means of making predictions and of integrating focus area results into a comprehensive understanding of the Earth system. Modeling and analysis requirements are diverse, encompass a multiplicity of spatial and temporal scales, and involve a hierarchy of models from comprehensive, global, Earth system models to local, more process-oriented models.

The major elements of the modeling and analysis effort within NASA's Earth science research program are:

- Create data assimilation capabilities for available diverse data types;
- Develop computational modeling capabilities for research focus areas; and
- Participate in national and international scientific assessments.

During the initial Earth Observing System (EOS) implementation, NASA developed a number of critical modeling capabilities including data assimilation and tools for assessing long-term climate and global ozone change. In addition, NASA led an interagency effort to develop a framework for model coupling to enable Earth system simulation, analysis, and prediction. As EOS data became available, modeling tools saw increasing use for capturing and summarizing observations to understand Earth system processes.

The development of comprehensive models and the reconciliation of model predictions with observations is an iterative process, comprising process model development, coupling of model components, and testing to identify inconsistencies or data inadequacies. The result is a steadily improving predictive capability with regularly evaluated uncertainties. Improved models in turn clarify observational goals and metrics.

2.3.1 Exploring Interactions within the Earth System

In order to explore interactions within the Earth system, NASA:

- Links Earth system component models;
- Evaluates and constrains models through measurement comparisons and model assimilated data; and
- Characterizes key component interactions through model analysis.

Linking models is a major challenge requiring well-studied component models as well as sufficient understanding of the processes that link the components in nature, particularly boundary-layer processes that control the exchanges of momentum, energy, water, and trace chemicals. An incremental strategy will be used to link increasingly complex component models at various stages of scientific inquiry and to assure a smooth progression in state-of-the-art Earth system models within, but challenging, the limitations of computational resources.

Satellite remote sensing data coupled with expanding surface and suborbital measurements are driving models to higher spatial and temporal resolutions. But coupling models at aggressively higher resolutions is challenging. Using new observations within models is often a difficult step as well. Interactions between components occur with varying temporal and spatial scales, and nonlinearities and feedbacks can complicate scale issues. In many cases, totally new approaches to data assimilation and analysis as well as modeling are needed.

2.3.2 Distinguishing Natural from Human-Induced Change

The attribution of environmental change is a key goal in producing predictions for decision support. Differences in the spatial and temporal characteristics of natural and hu-

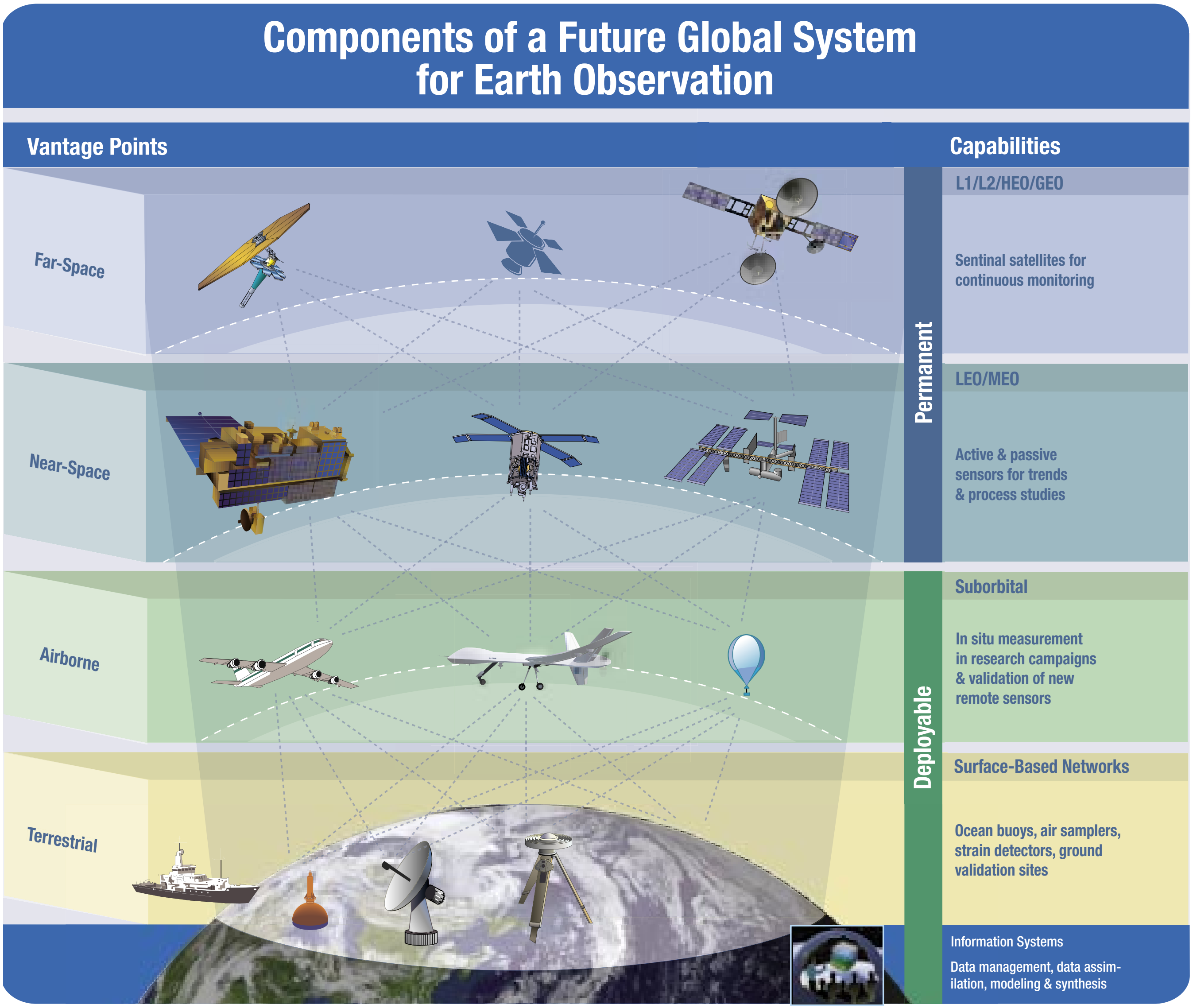
Table 2.3

GCOS climate monitoring principles.

Effective monitoring systems for climate should adhere to the following principles adopted by the Conference of the Parties to the UN Framework Convention on Climate Change through Decision 5/CP.5 of COP-5 at Bonn in November 1999:

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.
2. A suitable period of overlap for new and old observing systems is required.
3. T -
   tinent to interpreting data (i.e., metadata) should be documented and treated with the same care as the data themselves.
4. The quality and homogeneity of data should be regularly assessed as a part of routine operations.
5. Consideration of the needs for environmental and climate-monitoring products and assessments should be integrated into national, regional, and global observing priorities.
6. Operation of historically-uninterrupted stations and observing systems should be maintained.
7. High priority for additional observations should be focused on data-poor regions, poorly-observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution.
8. Long-term requirements, including appropriate sampling frequencies, should be specified to network designers, operators, and instrument engineers at the outset of system design and implementation.
9. The conversion of research observing systems to long-term operations in a carefully-planned manner should be promoted.
10. Data management systems that facilitate access, use, and interpretation of data and products should be included as essential elements of climate monitoring systems.

Figure 2.9



man-induced forcings can be subtle but are resolvable given sufficiently accurate and precise measurements coupled with robust models. The NASA strategy for differentiating forcings within the Earth system includes:

- Characterize and understand model sensitivities to forcings;
- Utilize modeling tools to analyze and ascribe trends; and
- Improve estimates of environmental variability from models.

A major issue for both seasonal and long-term climate change studies is the sensitivity of models to aerosol forcing. Improved aerosol radiative parameterizations within a number of climate models are providing better understanding of the range of likely sensitivities. Anticipating a wealth of relevant global data from current and planned satellite instruments, NASA will continue to accelerate work in this area. In addition, increasing emphasis will be placed on studies of model sensitivity to solar forcing.

Historical data reanalysis using assimilation systems is very useful for diagnosis of variability in short-term climate, but there are deficiencies in this approach. For example, momentum, heat, and moisture budgets do not balance. In regions such as tropical oceans or Arctic sea ice where important feedbacks occur, atmospheric reanalysis products are poor because they are less constrained by data and more influenced by uncertain parameterizations. Hence, the challenges for the next reanalysis products are to: (1) extract physical variability and trends from an array of artifacts including changes in the observing system or processing algorithm, (2) identify sensitivities associated with model approximations and parameterizations, and (3) increase accuracy so that they can be a tool to be used together with the satellite data for improving climate models. Concerted attacks on these issues, drawing on expertise across the science focus areas, is critical to progress.

2.3.3 Understanding and Predicting the Consequences of Earth System Change

NASA's approach to Earth system predictions includes:

- Construction of increasingly sophisticated predictive models;
- Utilization of assimilation systems to facilitate model predictions;
- Development and application of prediction accuracy metrics; and
- Conduct of model-based predictions and assessments.

Coupled Model Development.

As the interactions between various system components are characterized, NASA Earth science research will pursue fully-coupled models that include the full range of physical, chemical, and biological processes occurring within the Earth system. Such comprehensive models are conceivably needed to identify and assess the nonlinear impacts of the combined interactions and feedback processes that operate within the Earth system. Future, fully-coupled models should also be capable of simulating multiple spatial and temporal scales, given the great interest in both the scientific and policy communities for information across a wide range of scales. Such coupled models would be especially useful for regional and global assessments of future environmental trends and would help document the full diversity of expected changes in the total Earth system. Variable grid and nested models may play an important role in allowing for high spatial resolution without sacrificing computational efficiency.

The integration and coupling of various system components, however, is a daunting task unless there is coordination in development and a concerted effort to adhere to software standards. NASA supports the Earth System Modeling Framework (ESMF), which allows different modeling and assimilation groups to leverage common software tools not only for efficient development and transition to new computing architectures, but also for efficient integration and coupling. Future developments in this national collaboration will provide an environment to facilitate use of the various models under ESMF and so make models readily available to support focus area science.

Assimilation Systems

Data assimilation provides powerful constraints on predictive models by establishing reliable initializations. In assimilation, models are used to synthesize diverse in situ and satellite data streams into a single product that combines the strengths of each data set and of the model itself. The need to generate initialization fields for Numerical Weather Prediction has driven the direction of atmospheric assimilation development. Ocean assimilation products are now emerging to initialize ocean weather forecasts and seasonal predictions with coupled models as well as to improve estimates of ocean climate. Satellite altimetry makes global state estimation both feasible and meaningful. Land data assimilation is also emerging, stimulated by the availability of satellite-derived soil moisture and surface temperature.

There are many demands for data-constrained model integrations. Table 2.4 summarizes major products of model analyses that incorporate satellite and numerous surface observations. First, they are used as initial conditions for model predictions. Weather forecasts depend on the initial state of the fast components; climate projections out to a decade or more depend on the initial state of the "slow" ocean, cryosphere, and terrestrial components. Second, they are used for diagnostics of the historical climate record. Despite current limitations, assimilated fields provide the most internally consistent data sets for understanding how the climate system behaves, how natural perturbations (e.g., El Niño or the North Atlantic Oscillation) disrupt climate patterns, how extreme events are related to this variability, and how various subsystems interact. Third, assimilation analyses may serve as input to applications models of, for example, regional weather and air quality forecasting, agricultural and crop modeling, public health studies. Fourth, assimilation analyses are used as input to satellite data retrievals or to improve estimates of other satellite observed variables. Fifth, assimilation analyses can be used to infer unobserved variables. Examples of this are vertical wind speed, which is strongly related to cloudiness properties, heating, and dynamics. and the estimate of ocean subsurface temperature and salinity structure derived from surface altimetry. Sixth, assimilation plays an essential role in defining observing system requirements through observing system experimentation.

Prediction Metrics

Prediction accuracy metrics are important measures of success in Earth science. While weather prediction has a long history of deriving and using such accuracy metrics, climate science is only beginning to explore this area. Limits on weather prediction (an initial value problem) are fairly well known, but limits on climate prediction (a boundary condition problem) remain largely unknown. Noise in weather data and in predictions increases with increasing time and space scale. Noise in climate data and predictions decrease with increasing time and space scale. These differences suggest that prediction skill metrics will vary strongly with the variable, lead time, and space scale. An important element of quantifying the prediction skill metric is identifying the controls. For example, how accurately must a model predict annual mean global, zonal, and regional cloud and radiation in order to constrain cloud feedback to reduced levels of uncertainty? The Earth science modeling program will work to improve the definition of prediction metrics, especially for the climate modeling area. For many time scales, model predictions must be verified against data in retrospective mode.

Predictions and Assessments

The atmospheric chemistry community has a long history of supporting assessments of the impacts of various disturbances on the atmospheric environment. The most widely known are the periodic Scientific Assessments of Ozone Depletion, carried out on behalf of the World Meteorological Organization and the United Nations Environment Programme as well as the assessment of climate forcing factors on behalf of the Intergovernmental Panel on Climate Change. NASA continues to support national and international assessments involving modeling and analysis with emphasis on chemical-transport models for ozone assessments, the global carbon cycle as it controls atmospheric CO_2 and CH_4, and global climate models.

Model simulations, incorporating given scenarios for changes in forcing, are the most compelling means for estimating the potential impacts of changes in the global environment. For these assessments, both retrospective, diagnostic simulations of the past evolution of the global environment, and prognostic studies to simulate potential future responses to alternative changes in forcing provide the scientific information required by responsible authorities. Seasonal prediction with coupled models provides a capstone for coupled models and assimilation systems in much the same way as weather prediction has done for atmospheric models and atmospheric assimilation.

2.4.4 Modeling Resources

As described above and in the separate science focus area discussions, NASA Earth science research requires a number of modeling approaches ranging from regional- to global-scale, data-constrained to free-running, and from single component to coupled. In moving from process to component to fully-coupled interactive models, NASA plans to significantly increase computational capability over the next decade. NASA anticipates the following priorities for computational resources:

- Model-data comparisons and data assimilation;
- Demonstration of coupled model performance; and
- Model predictions and science assessments.

Research in these areas will be selected through competitive solicitation; however, there is a continuing commitment to maintain key NASA infrastructure for data assimilation and assessment. Major drivers of computational resources will include the handling of increasingly large satellite data sets, the creation of increasingly large model codes to represent different system components, and the push toward models of higher spatial and temporal resolution in support of assessments. Specific resource decisions will be made in concert with focus area requirements and national and international assessment needs.

Table 2.4. Modeling products.

Parameter/ Question	Implementation Detail	Technical Readiness	OperationalPo-tential thru 2010	Partnership Potential
10-day weather forecasts including space shuttle mission support (P1)	10-30 km resolution global domain; extend model top to thermosphere (130 km)	30 km global ready by FY04; space shuttle support related development required	Yes	NCEP, NCAR, and ECMWF
Severe local storms (P1)	1-5 km limited area and nesting with global domain within a unified modeling system to be developed	Development of a unified regional-global modeling system required	Not cur-rently feasible; development & operational dem-onstration needed	NCEP and FSL
Hurricanes and typhoons (P1)	Minimum resolution of 55 km needed; improved initialization methodology	Track prediction ready at present; intensity prediction by 2008	Yes	National Hurricane Center; Joint Ty-phoon warning center
Local & global long-range prediction of pollutants (P3)	A comprehensive trop-strat chemistry to be implemented; high-resolu-tion sources/sinks data needed	Scientific development required; passive pollutants ready at present	Yes	Home land security dept; EPA
Winter snow storms (P1)	55 km minimum; prefer-ably at 30 km or higher	Improved land modeling & as-similation capability required	Yes	NCEP
Floods (P1, P5, P6)	Regional-global nesting required with current computing capability- high resolution topography, landcover models, rainfall, soil moisture	High-resolution (30 km or higher) global model required, High resolution topography, soil moisture, land cover data needed in addition to rainfall info	Yes	NOAA, USGS, FEMA
30-90 days forecasts (P1)	55 km or higher resolution required to be able to predict anomalies in tropi-cal storms and winter snowstorms	Coupling to ocean, dynamic sea ice, and high-resolution land model	Yes	NOAA
Droughts (P1, P5)	Impact of land usage change to be studied	Improved land modeling & assim-ilation need to be demonstrated	Yes	NOAA
Atmospheric chemistry change assessment (P3)	A comprehensive trop-strat chemistry to be implemented; bio-chemistry in land model to be developed	Scientific developments in cou-pling to atmospheric chemistry and bio-chemistry required	Yes	NOAA, DOE
Chemistry-Climate change (P2, P3)	High resolution required to access regional impacts; cou-pling to high-resolution ocean model highly desirable	High resolution pending on efficient use of the available high-end computing platform	Yes	NOAA, DOE, NSF/NCAR
Global, seasonal pre-cipitation, and surface temperature forecasts with uncertainty estimates at 12-month lead times (P2)	Ensembles of Global, coupled ocean atmosphere sea-ice models	Demonstrated capability for 6-month forecast leads; multi-model ensembles needed to compensate for different biases in different models	Very high	NOAA
Global predictions of the like-lihood of extreme weather events associated with sea-sonal climate anomalies (P2)	Large ensembles of global coupled models	Demonstrated ability of simulat-ing the observed differences in probability distributions of wintertime storms over the U.S.	High	NOAA
Global seasonal soil moisture forecasts with uncertainty estimates at 12-month lead times and at regional scales (P2, P5)	Ensembles of high resolu-tion global, coupled ocean atmosphere sea-ice models	Demonstrated capability to initialize soil moisture distribu-tions, waiting for accurate soil moisture observations	Very High	Dept of Agriculture, Forestry service

Table 2.4 Continued

Parameter/ Question	Implementation Detail	Technical Readiness	OperationalPo-tential thru 2010	Partnership Potential
Global time series of forecasts of the state of the ocean (at 1/10 degree resolution) and the atmosphere (at 1/4 degree resolution) for 1 season for diagnostics and analysis (P2)	Ensembles of Global, coupled ocean atmosphere sea-ice models	Demonstrated capability atmospheric simulations at 1/3 degree, and coupled simula-tions with the AGCM at 1 degree and ocean at 1/3 degree.	Very high	NOAA universities
Global forecasts down-scaled for regional water management and agricul-tural applications (P5)	Ensembles of high resolution global, coupled models, with statistical methods to downscale for regional hydrology models	Developments underway	Medium to high	NOAA, universities
Projections of land cover and land use change (P4)	Ensembles of high resolution, coupled natural-human system models, with methods to accom-modate regional differences	Scientific developments required in coupling models of natural system behavior with models of human system behavior	Medium to low	USDA, NSF
Ecological Forecasts for resource management and human health (e.g, invasive species; harmful algal blooms) (P4)	Advanced ecosystem models incorporating the combined effects of changes in multiple, interacting factors and human system controls	Developments underway; scientific developments in integrating human system behavior in models required	Medium	NOAA, DOI, USDA, EPA
Projections of future atmospheric concentra-tions of CO_2 and CH_4 (P3)	Global observations of atm. column CO_2 and CH_4, and biomass ingested into coupled carbon-cli-mate-human system models	Technological demonstra-tions needed; Advances in coupling natural and human system models required	Medium	NOAA, DOE, NSF, USDA,
Projections of future changes in surface hydrological parameters (soil moisture, runoff, evapotranspiration) due to changes in land use and land cover. (P5)	global inventory of land cover and land use changes on the landscape, LCLUC ingested into terrestrial hydrology models.	development is underway, advances in coupling land use with hydrology models required	Low	NOAA, USGS, NSF, USDA
Earthquake forecasting (P6)	Near realtime Global topography surface deformation and fault maps, sediment cover estimates-electromagnetic research, crustal rheology, and stress estimates, new modeling algorithms, data mining, fault interactions, TIR imaging	Poor- t InSAR and LiDAR mapping not available	Possible if proper data bases developed. Data mining predictive algorithm appears very successful.	USGS/NSF/FEMA-international collaborations
Volcano forecasting (P6)	Near realtime Global topography surface deformation and fault maps, sediment cover estimates-electromagnetic research, crustal rheology, and stress estimates, new modeling algorithms, data min-ing, fault interactions, TIR	Good; Demonstrationsuch as Pinatubo have been successful-challenge is long term forecasting	Desired	USGS/NSF/FEMA-international collaborations
Ice sheet change (P6)	Global surface deformation maps	Good; awaiting demonstration	Desired	USGS/NSF/NOAA